US010616963B2

(12) **United States Patent**
Scott et al.

(10) **Patent No.: US 10,616,963 B2**
(45) **Date of Patent: Apr. 7, 2020**

(54) **APPARATUS AND METHODS FOR DETECTING DEFROSTING OPERATION COMPLETION**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 296 days.

(21) Appl. No.: **15/454,345**

(22) Filed: **Mar. 9, 2017**

(65) **Prior Publication Data**

US 2018/0042073 A1 Feb. 8, 2018

(30) **Foreign Application Priority Data**

Aug. 5, 2016 (EP) 16306022

(51) **Int. Cl.**
H05B 6/68 (2006.01)
H05B 6/62 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H05B 6/688*** (2013.01); ***H05B 6/62*** (2013.01); ***H05B 6/645*** (2013.01); ***H05B 6/6467*** (2013.01); ***H05B 6/664*** (2013.01)

(58) **Field of Classification Search**
CPC H05B 6/6438; H05B 6/705; H05B 6/688; H05B 6/6467; H05B 6/62; H05B 6/645;
(Continued)

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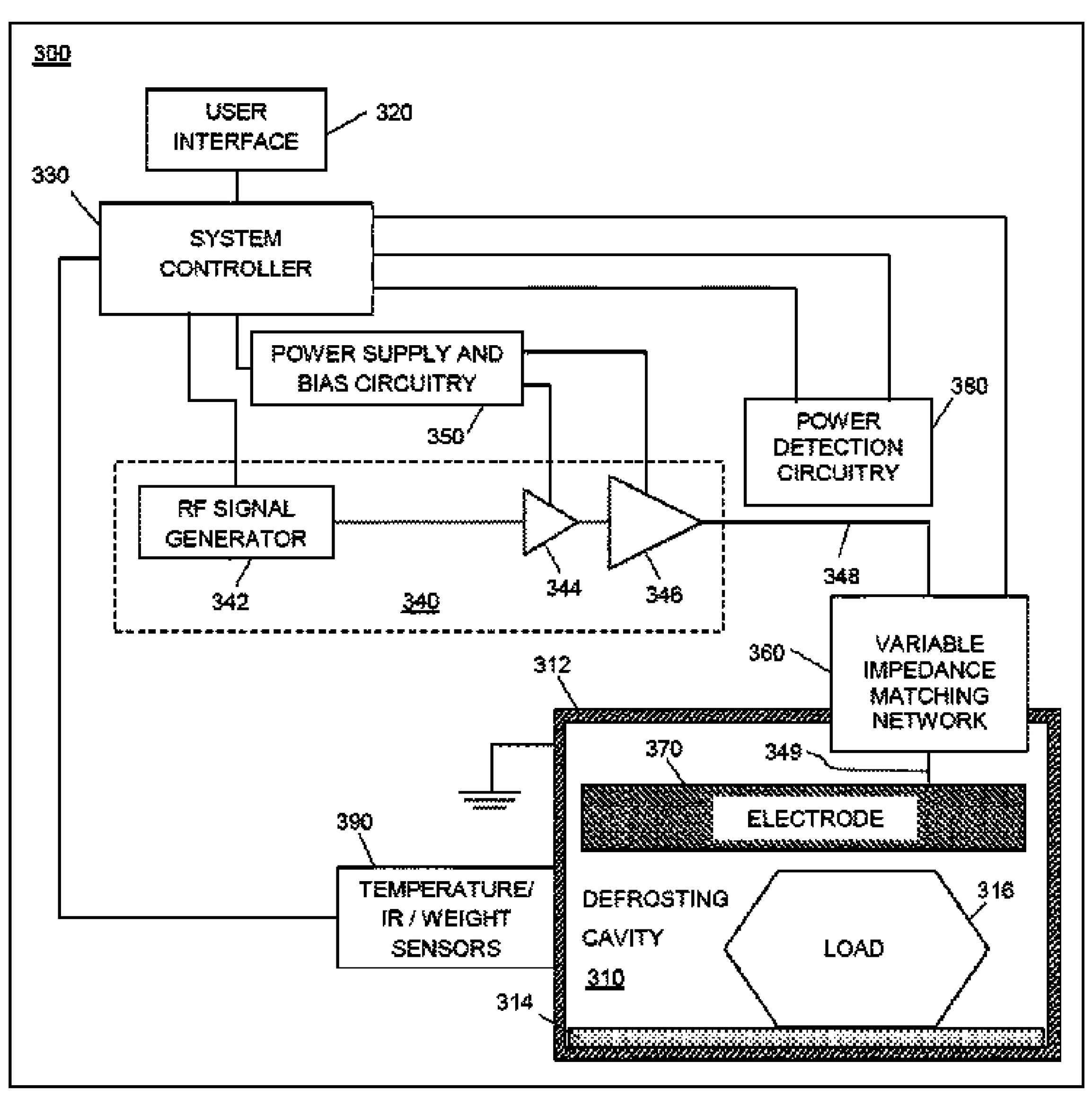
(57) **ABSTRACT**

A defrosting system includes an RF signal source, an electrode proximate to a cavity within which a load to be defrosted is positioned, and a transmission path between the RF signal source and the electrode. The system also includes power detection circuitry coupled to the transmission path and configured repeatedly to take forward and reflected RF power measurements along the transmission path. A system controller repeatedly determines, based on the forward and reflected RF power measurements, a calculated rate of change, and repeatedly compares the calculated rate of change to a threshold rate of change. When the calculated rate of change compares favorably with the threshold rate of change, the RF signal source continues to provide the RF signal to the electrode until a determination is made that the defrosting operation is completed, at which time the RF signal source ceases to provide the RF signal to the electrode.

14 Claims, 11 Drawing Sheets



(51) **Int. Cl.**
H05B 6/64 (2006.01)
H05B 6/66 (2006.01)

(58) **Field of Classification Search**
CPC . H05B 6/664; H05B 6/46; H05B 6/48; H05B 6/50; H05B 6/68; H03H 7/40; F25D 23/12; F25D 21/08
USPC 219/703, 704, 710, 711, 712
See application file for complete search history.

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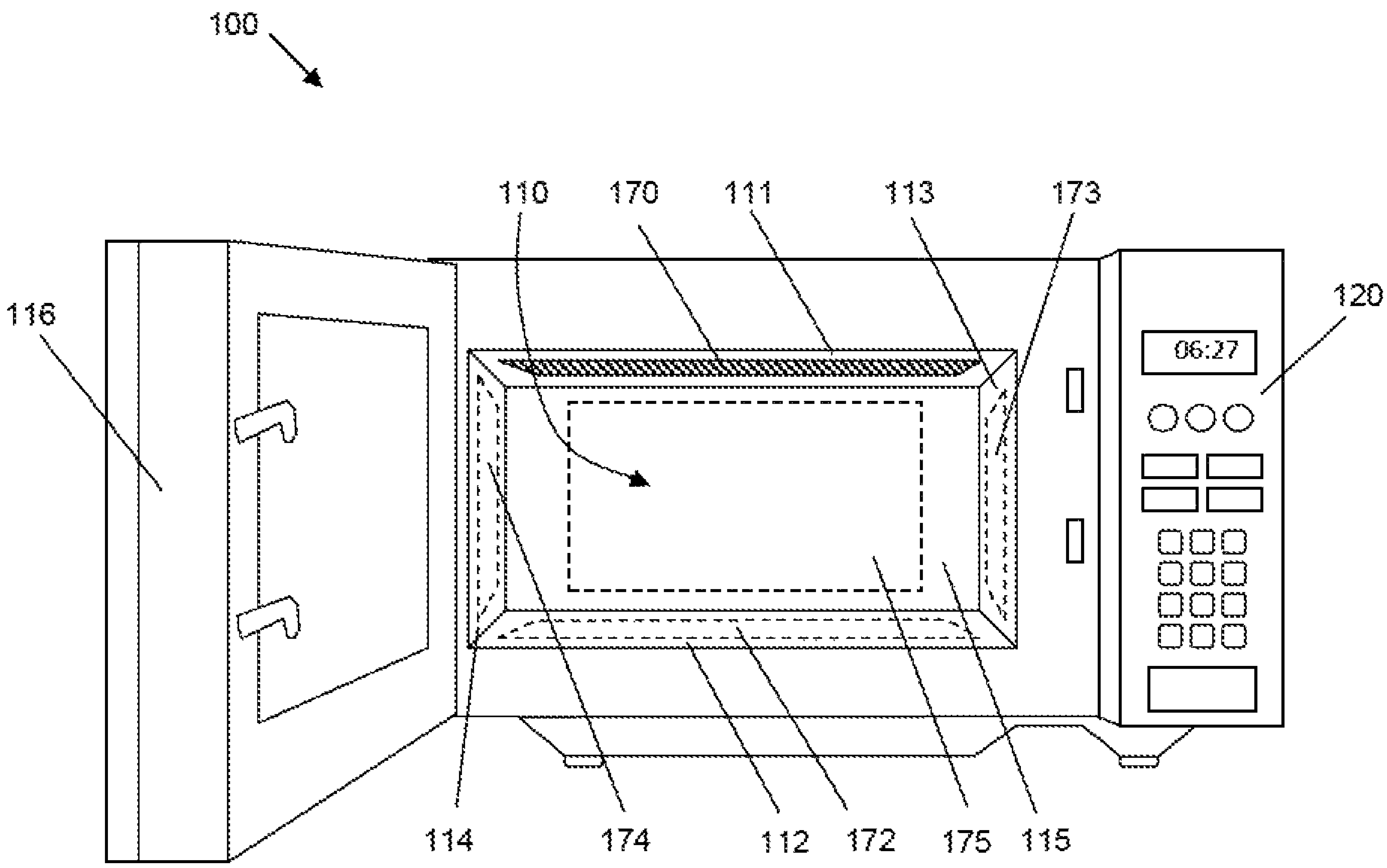

FIG. 1

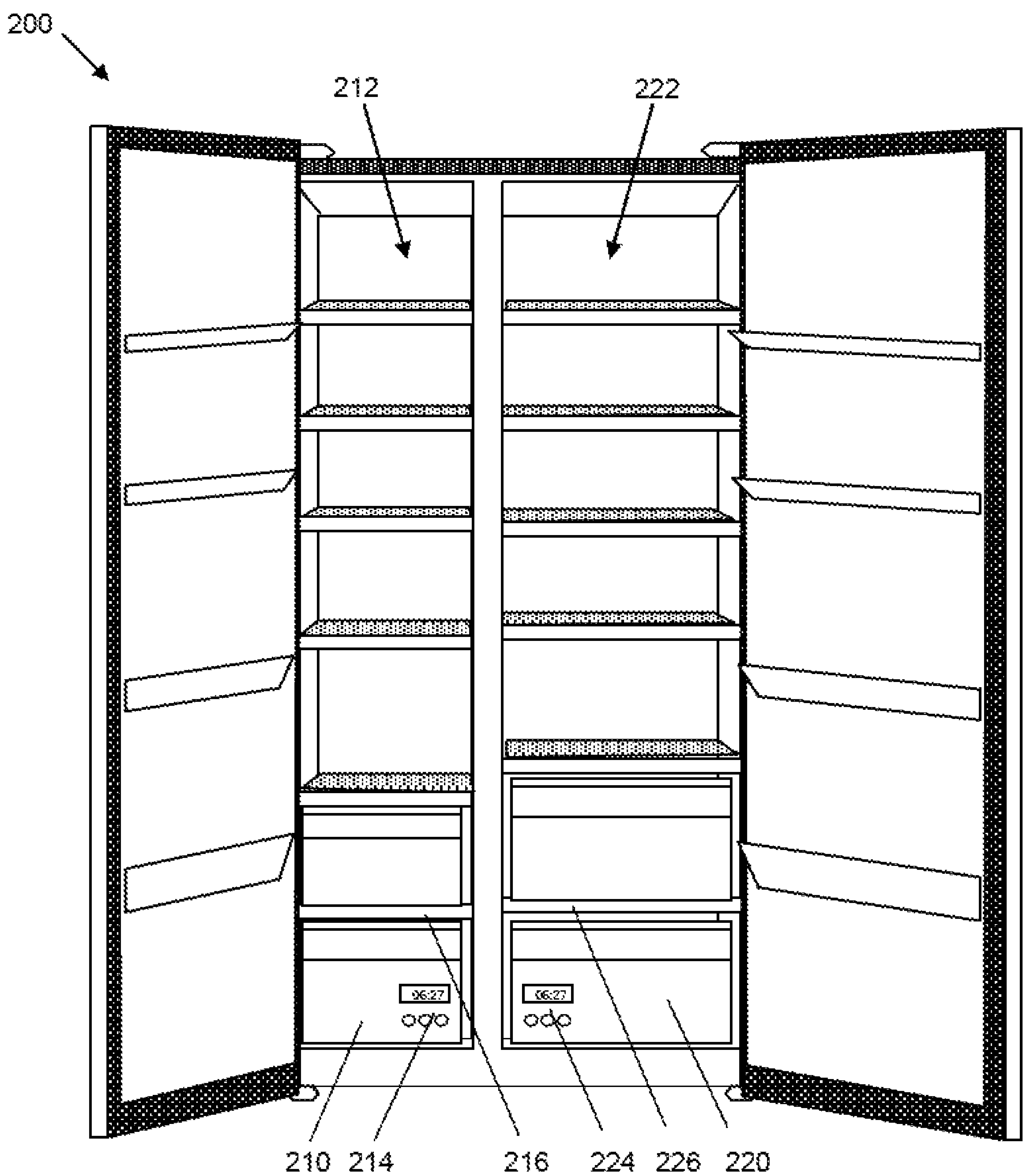

FIG. 2

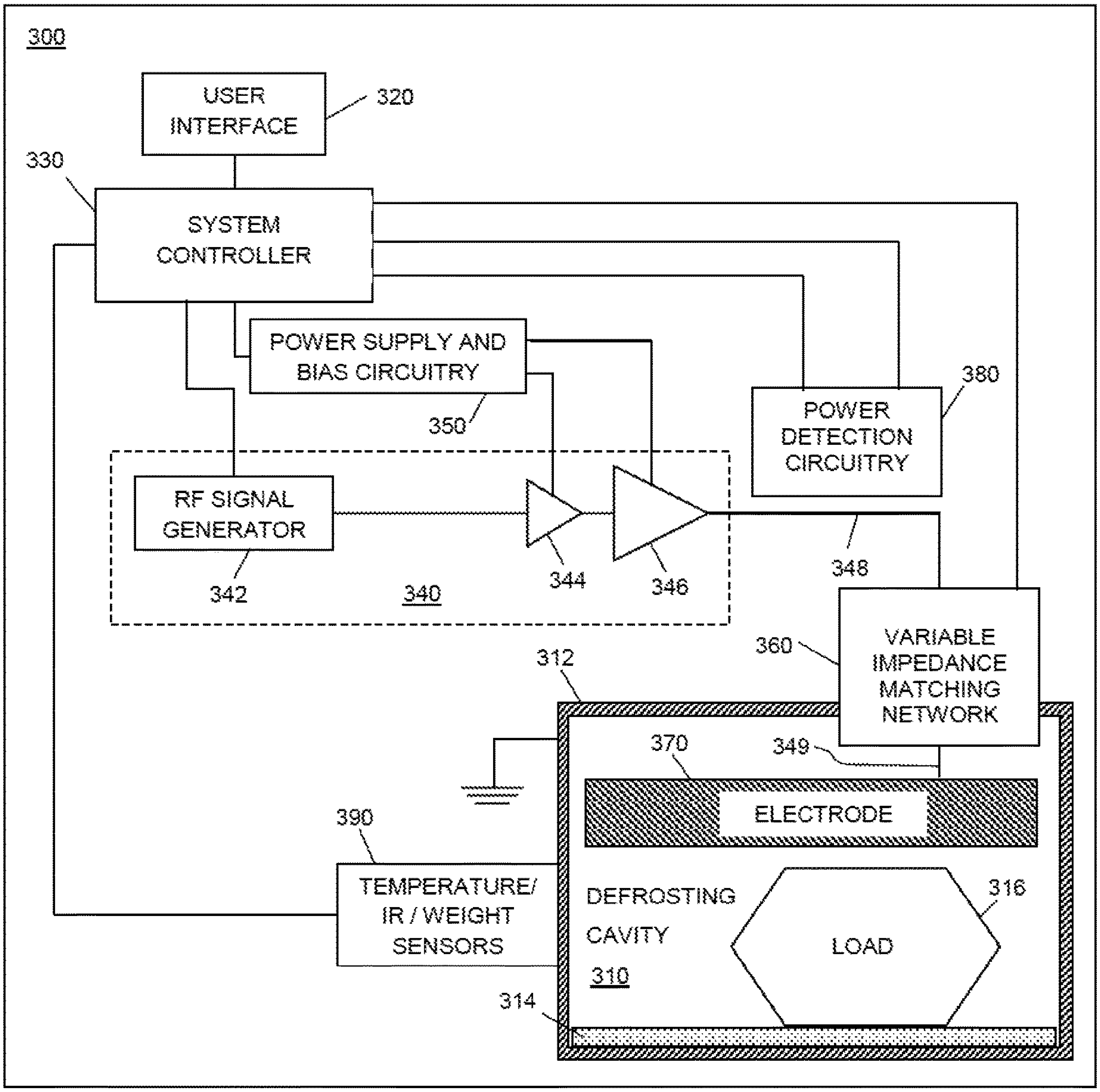
300
USER INTERFACE
320
330
SYSTEM CONTROLLER
POWER SUPPLY AND BIAS CIRCUITRY
350
380
POWER DETECTION CIRCUITRY
RF SIGNAL GENERATOR
342
340
344
346
348
360
VARIABLE IMPEDANCE MATCHING NETWORK
312
370
349
ELECTRODE
390
TEMPERATURE/ IR / WEIGHT SENSORS
DEFROSTING CAVITY
310
316
LOAD
314

FIG. 3

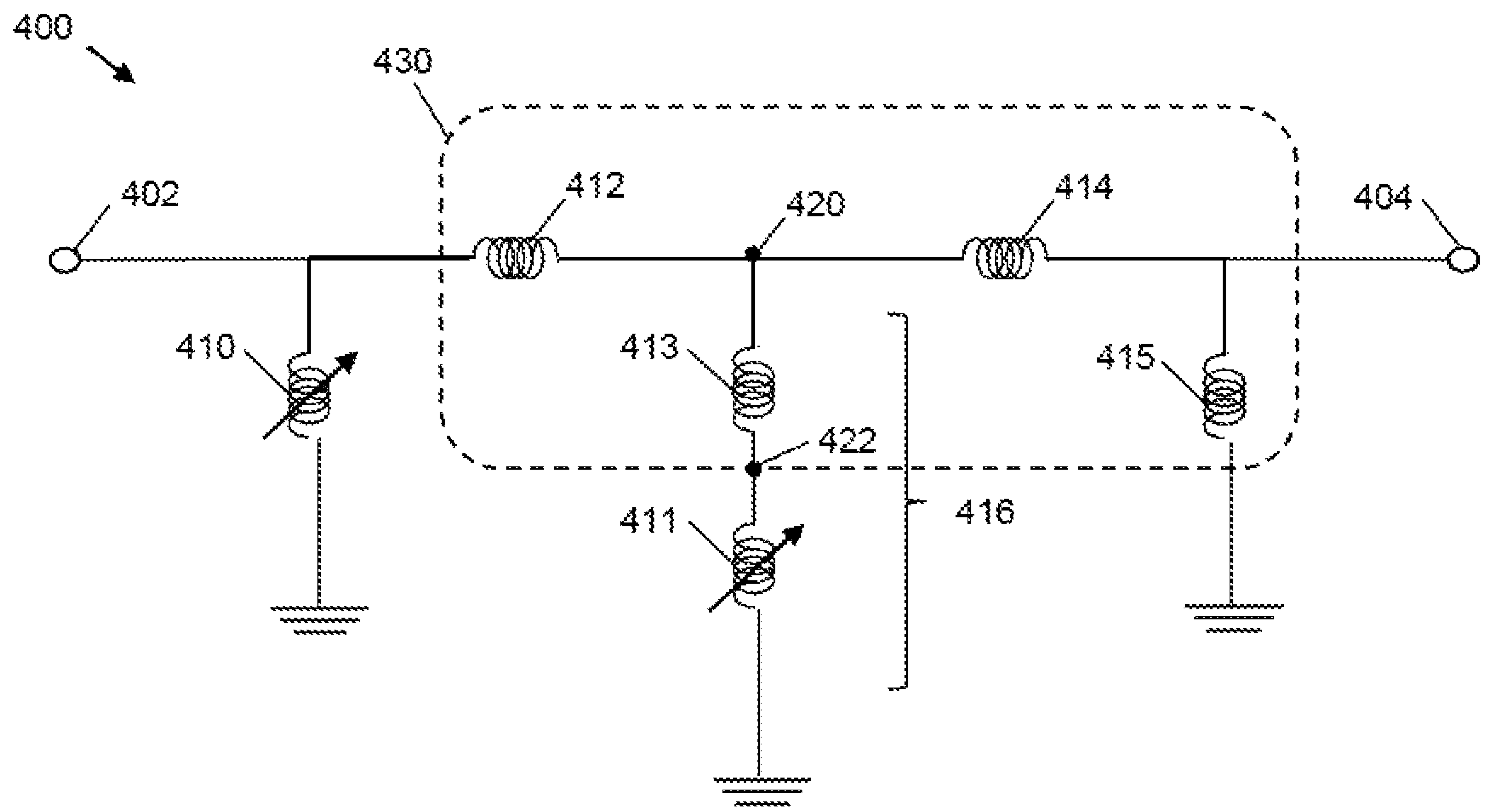
400
430
402
412
420
414
404
410
413
415
422
411
416

FIG. 4

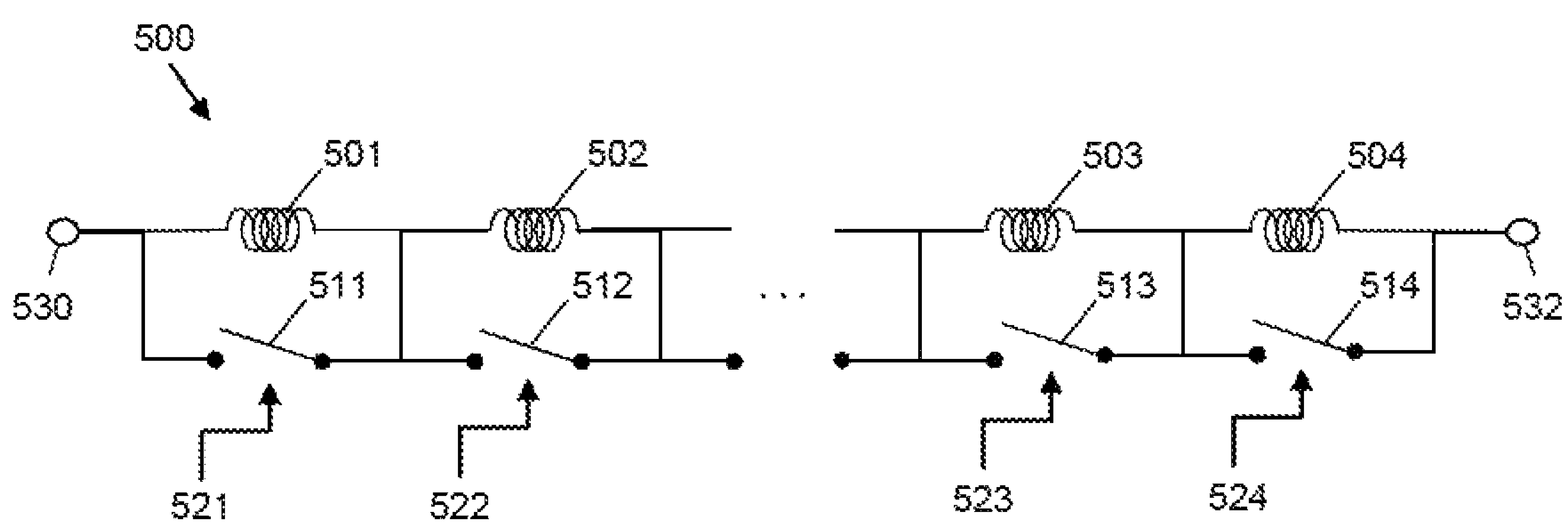
500
501
502
503
504
530
511
512
513
514
532
521
522
523
524

FIG. 5

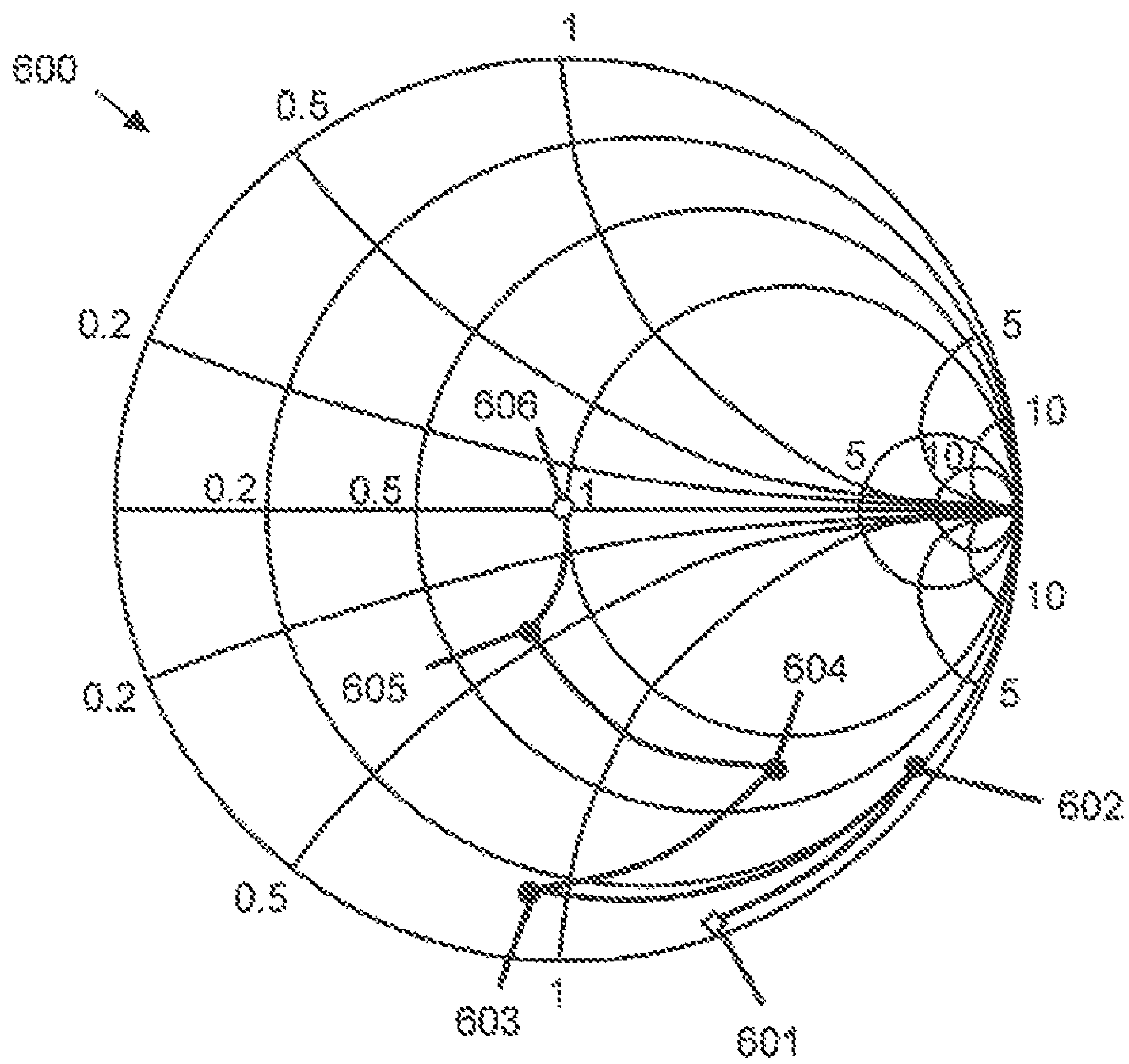

FIG. 6

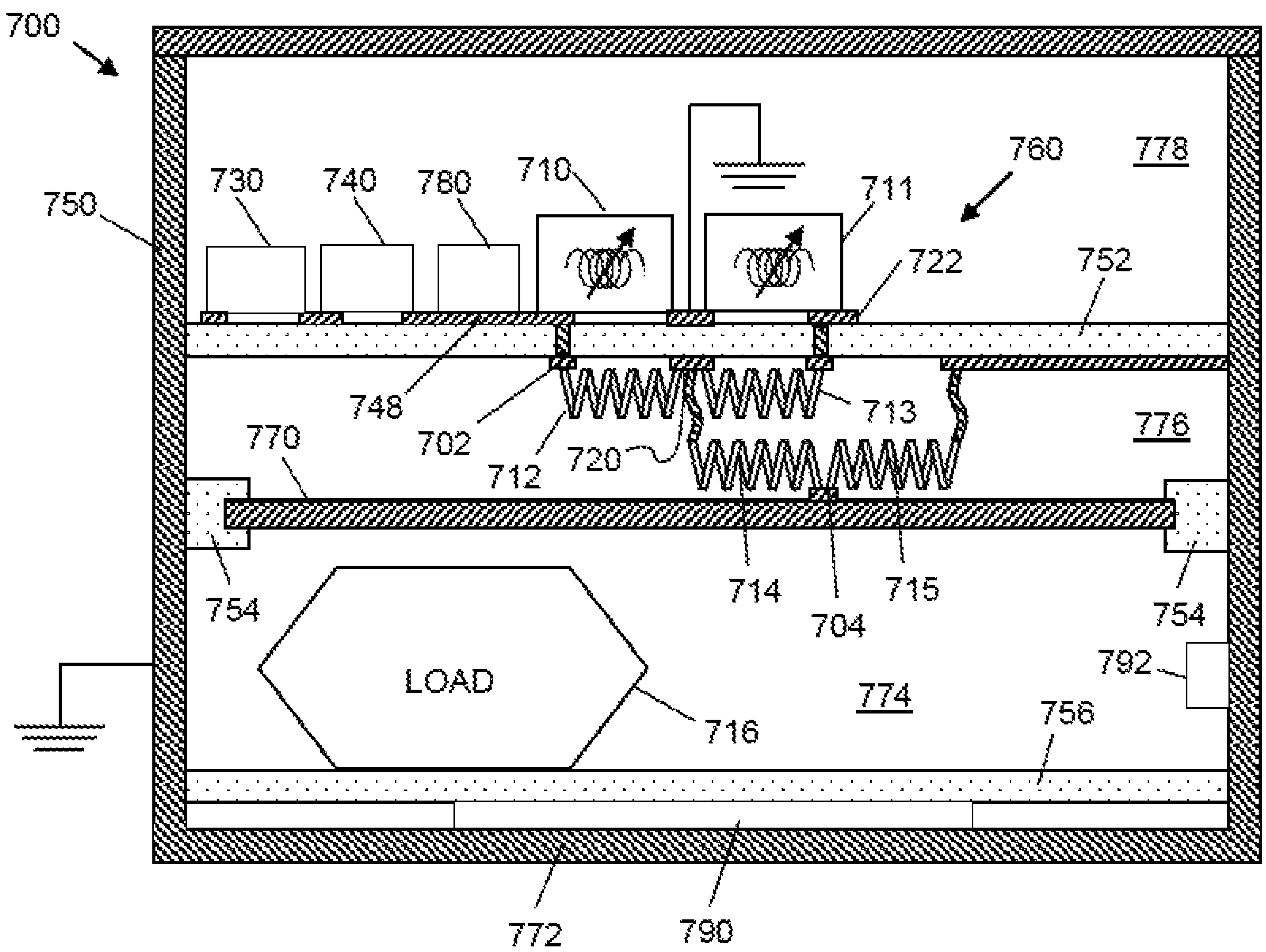
700
750
730
740
780
710
711
760
778
722
752
748
702
713
776
770
712
720
754
714
704
715
LOAD
716
774
792
756
772
790

FIG. 7

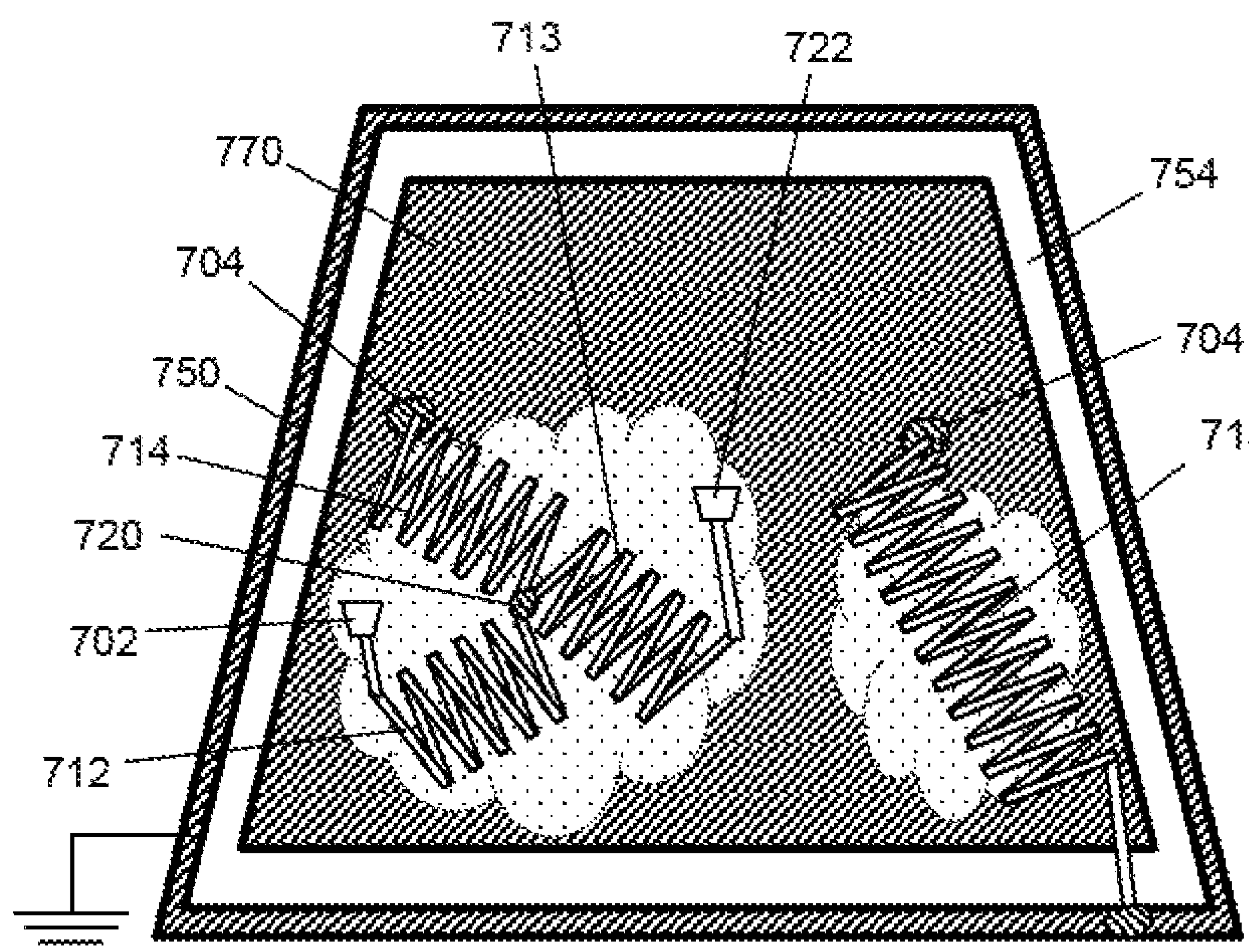
713
722
770
754
704
750
714
720
702
712
715

FIG. 8

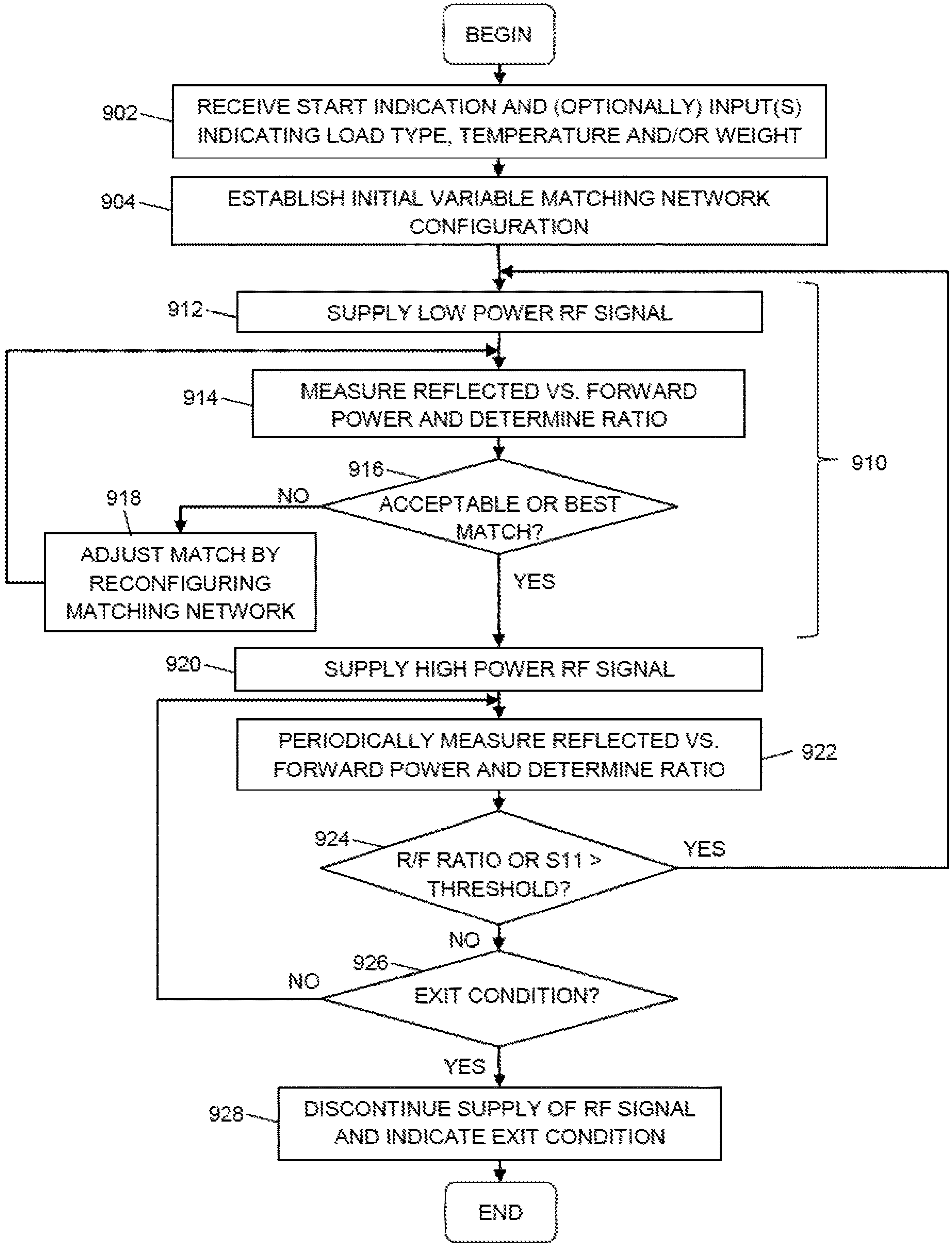
BEGIN
902
RECEIVE START INDICATION AND (OPTIONALLY) INPUT(S) INDICATING LOAD TYPE, TEMPERATURE AND/OR WEIGHT
904
ESTABLISH INITIAL VARIABLE MATCHING NETWORK CONFIGURATION
912
SUPPLY LOW POWER RF SIGNAL
914
MEASURE REFLECTED VS. FORWARD POWER AND DETERMINE RATIO
916
ACCEPTABLE OR BEST MATCH?
NO
918
ADJUST MATCH BY RECONFIGURING MATCHING NETWORK
YES
910
920
SUPPLY HIGH POWER RF SIGNAL
PERIODICALLY MEASURE REFLECTED VS. FORWARD POWER AND DETERMINE RATIO
922
924
R/F RATIO OR S11 > THRESHOLD?
YES
NO
926
EXIT CONDITION?
NO
YES
928
DISCONTINUE SUPPLY OF RF SIGNAL AND INDICATE EXIT CONDITION
END

FIG. 9

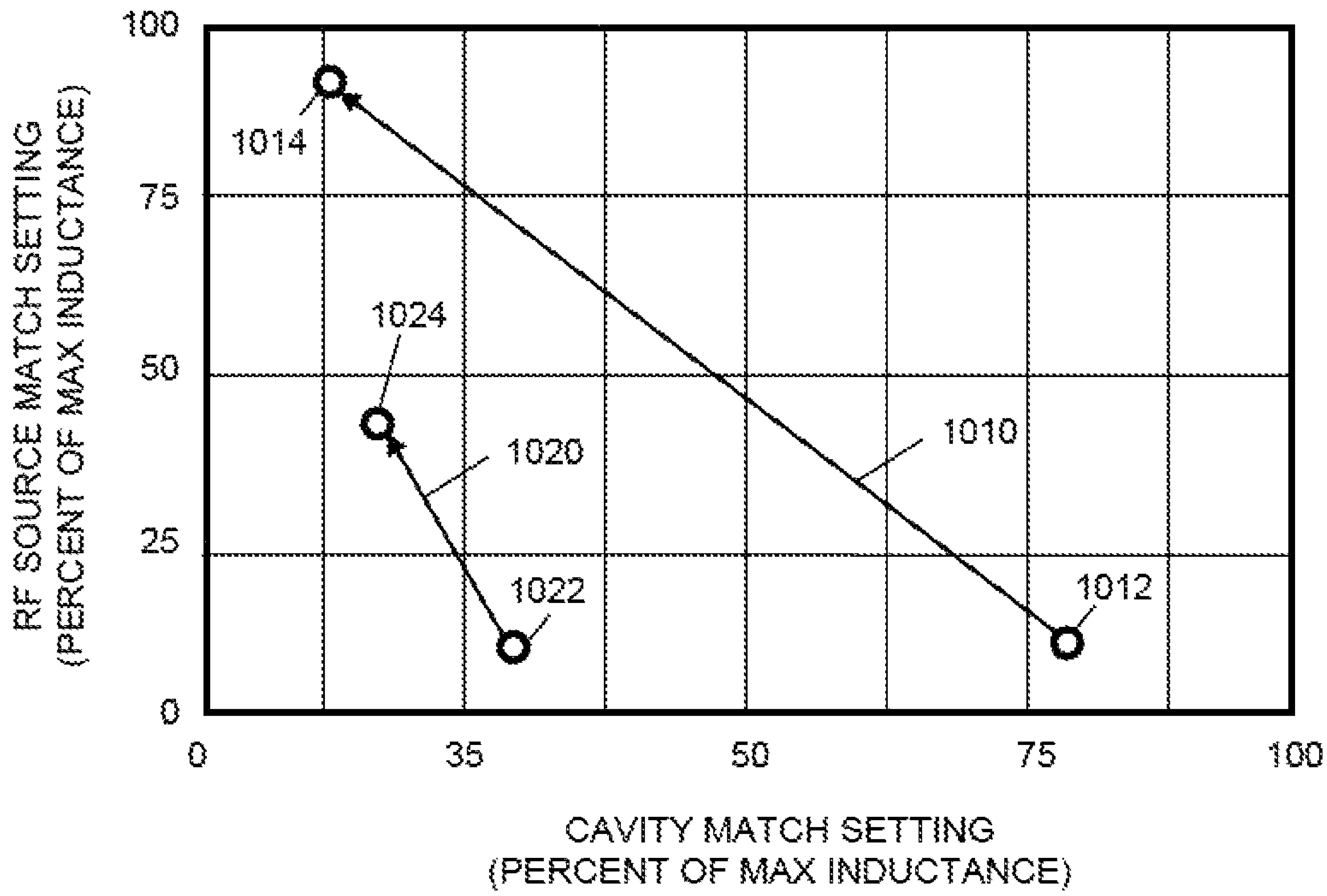
100
75
50
25
0
RF SOURCE MATCH SETTING
(PERCENT OF MAX INDUCTANCE)
1014
1024
1020
1010
1022
1012
0
35
50
75
100
CAVITY MATCH SETTING
(PERCENT OF MAX INDUCTANCE)

FIG. 10

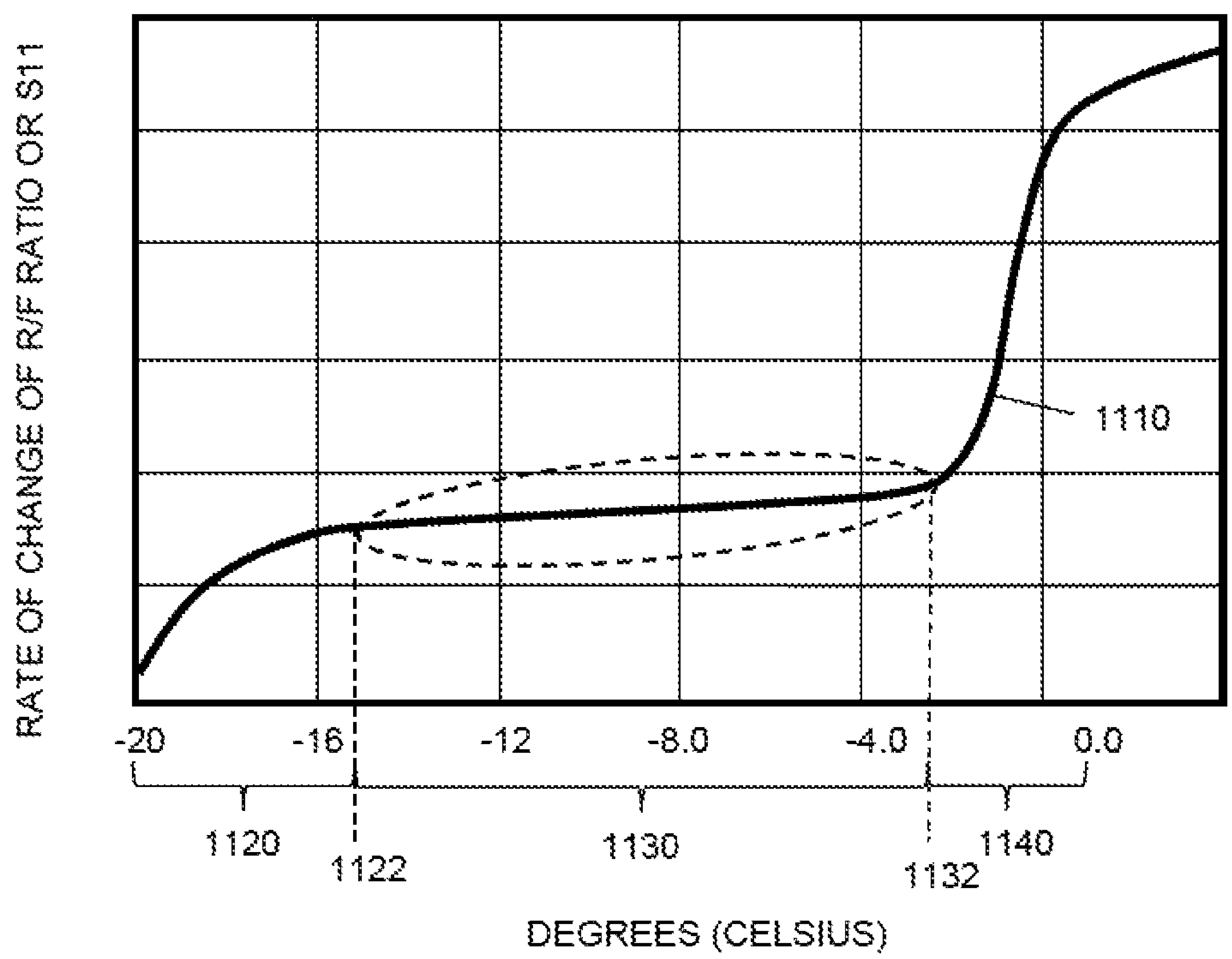
RATE OF CHANGE OF R/F RATIO OR S11
1110
-20
-16
-12
-8.0
-4.0
0.0
1120
1122
1130
1132
1140
DEGREES (CELSIUS)

FIG. 11

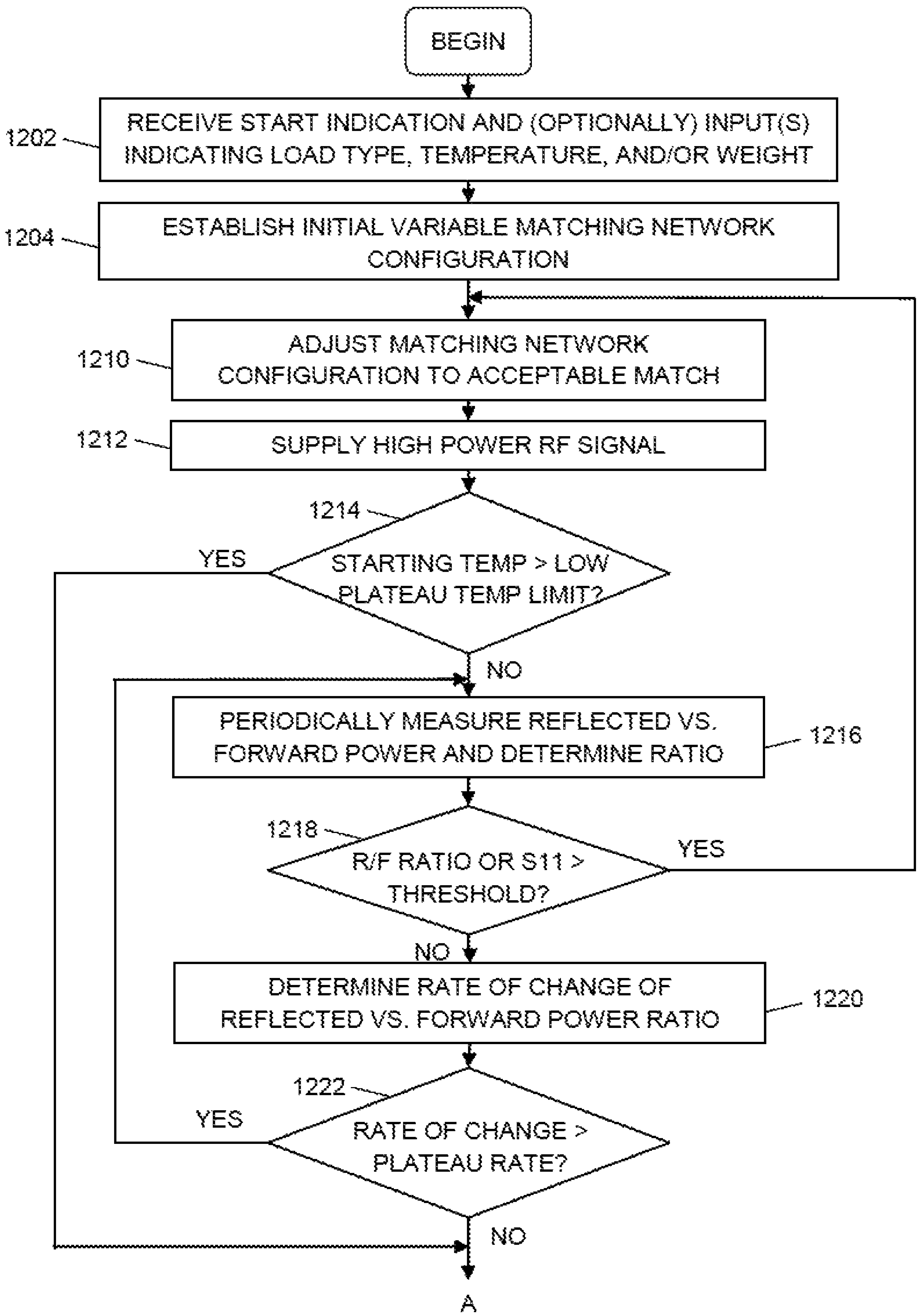
BEGIN
1202
RECEIVE START INDICATION AND (OPTIONALLY) INPUT(S) INDICATING LOAD TYPE, TEMPERATURE, AND/OR WEIGHT
1204
ESTABLISH INITIAL VARIABLE MATCHING NETWORK CONFIGURATION
1210
ADJUST MATCHING NETWORK CONFIGURATION TO ACCEPTABLE MATCH
1212
SUPPLY HIGH POWER RF SIGNAL
1214
STARTING TEMP > LOW PLATEAU TEMP LIMIT?
YES
NO
PERIODICALLY MEASURE REFLECTED VS. FORWARD POWER AND DETERMINE RATIO
1216
1218
R/F RATIO OR S11 > THRESHOLD?
YES
NO
DETERMINE RATE OF CHANGE OF REFLECTED VS. FORWARD POWER RATIO
1220
1222
RATE OF CHANGE > PLATEAU RATE?
YES
NO
A

FIG. 12A

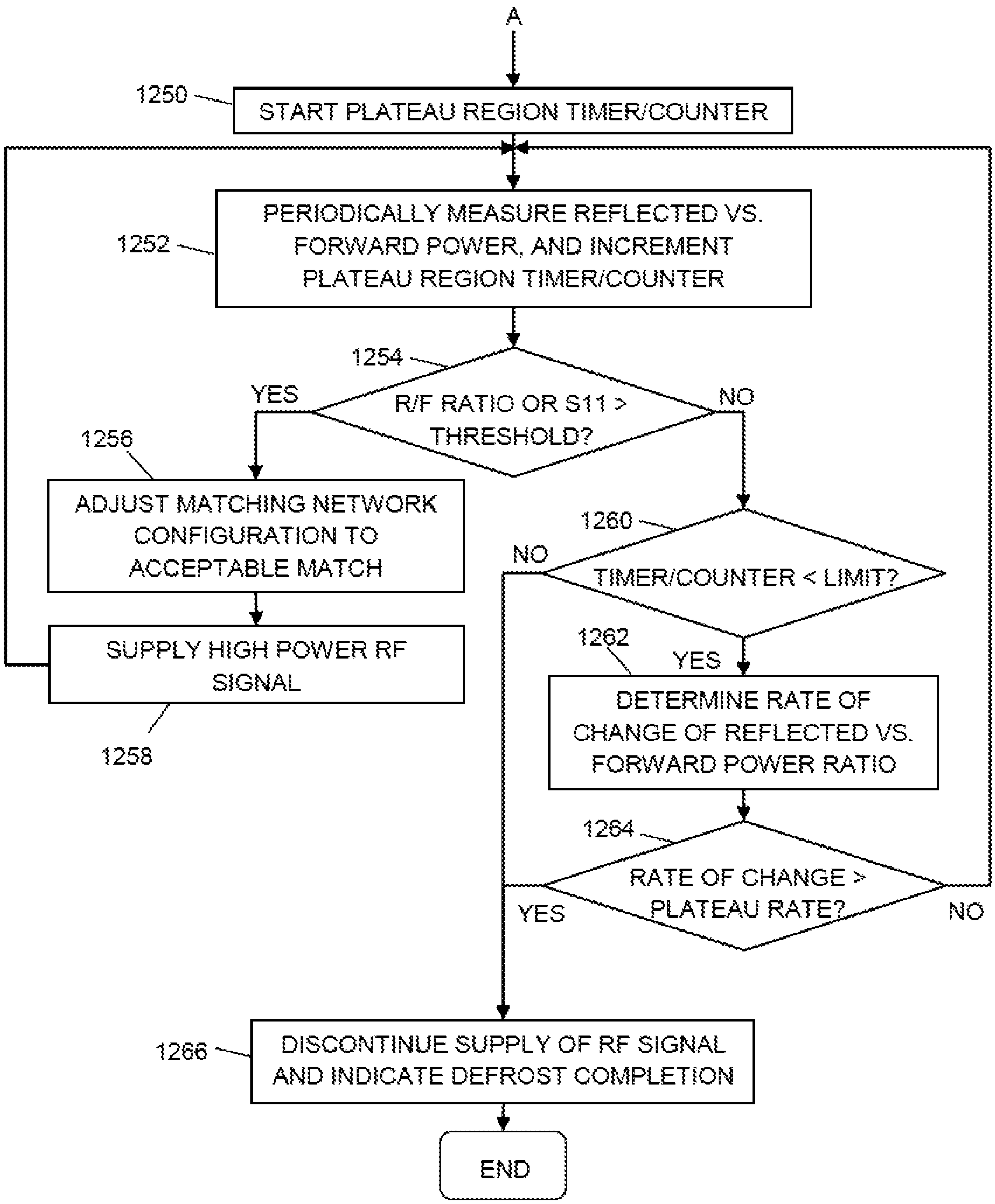
A
1250
START PLATEAU REGION TIMER/COUNTER
1252
PERIODICALLY MEASURE REFLECTED VS. FORWARD POWER, AND INCREMENT PLATEAU REGION TIMER/COUNTER
1254
R/F RATIO OR S11 > THRESHOLD?
YES
NO
1256
ADJUST MATCHING NETWORK CONFIGURATION TO ACCEPTABLE MATCH
SUPPLY HIGH POWER RF SIGNAL
1258
1260
TIMER/COUNTER < LIMIT?
NO
1262
YES
DETERMINE RATE OF CHANGE OF REFLECTED VS. FORWARD POWER RATIO
1264
RATE OF CHANGE > PLATEAU RATE?
YES
NO
1266
DISCONTINUE SUPPLY OF RF SIGNAL AND INDICATE DEFROST COMPLETION
END

FIG. 12B

APPARATUS AND METHODS FOR DETECTING DEFROSTING OPERATION COMPLETION

TECHNICAL FIELD

Embodiments of the subject matter described herein relate generally to apparatus and methods of defrosting a load using radio frequency (RF) energy.

BACKGROUND

Conventional capacitive food defrosting (or thawing) systems include large planar electrodes contained within a heating compartment. After a food load is placed between the electrodes and the electrodes are brought into contact with the food load, low power electromagnetic energy is supplied to the electrodes to provide gentle warming of the food load. As the food load thaws during the defrosting operation, the impedance of the food load changes. Accordingly, the power transfer to the food load also changes during the defrosting operation. The duration of the defrosting operation may be determined, for example, based on the weight of the food load, and a timer may be used to control cessation of the operation.

Although good defrosting results are possible using such systems, the dynamic changes to the food load impedance may result in inefficient defrosting of the food load. In addition, inaccuracies inherent in determining the duration of the defrosting operation based on weight may result in premature cessation of the defrosting operation, or late cessation after the food load has begun to cook. What are needed are apparatus and methods for defrosting food loads (or other types of loads) that may result in efficient and even defrosting throughout the load and cessation of the defrosting operation when the load is at a desired temperature.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the subject matter may be derived by referring to the detailed description and claims when considered in conjunction with the following figures, wherein like reference numbers refer to similar elements throughout the figures.

FIG. **1** is a perspective view of a defrosting appliance, in accordance with an example embodiment;

FIG. **2** is a perspective view of a refrigerator/freezer appliance that includes other example embodiments of defrosting systems;

FIG. **3** is a simplified block diagram of a defrosting apparatus, in accordance with an example embodiment;

FIG. **4** is a schematic diagram of a variable inductance matching network, in accordance with an example embodiment;

FIG. **5** is a schematic diagram of a variable inductance network, in accordance with an example embodiment;

FIG. **6** is an example of a Smith chart depicting how a plurality of inductances in an embodiment of a variable impedance matching network may match the input cavity impedance to an RF signal source;

FIG. **7** is a cross-sectional, side view of a defrosting system, in accordance with an example embodiment;

FIG. **8** is a perspective view of a portion of a defrosting system, in accordance with an example embodiment;

FIG. **9** is a flowchart of a method of operating a defrosting system with dynamic load matching, in accordance with an example embodiment;

FIG. **10** is a chart plotting cavity match setting versus RF signal source match setting through a defrost operation for two different loads;

FIG. **11** is a chart plotting temperature versus change in reflected-to-forward power ratio for a particular load; and

FIG. **12** (including FIGS. **12**A and **12**B) is a flowchart of a method of operating a defrosting system with automatic detection of the end of a defrosting operation, in accordance with an example embodiment.

DETAILED DESCRIPTION

The following detailed description is merely illustrative in nature and is not intended to limit the embodiments of the subject matter or the application and uses of such embodiments. As used herein, the words "exemplary" and "example" mean "serving as an example, instance, or illustration." Any implementation described herein as exemplary or an example is not necessarily to be construed as preferred or advantageous over other implementations. Furthermore, there is no intention to be bound by any expressed or implied theory presented in the preceding technical field, background, or the following detailed description.

Embodiments of the subject matter described herein relate to solid-state defrosting apparatus that may be incorporated into stand-alone appliances or into other systems. As described in greater detail below, exemplary defrosting systems are realized using a first electrode disposed in a cavity, an amplifier arrangement (including one or more transistors), an impedance matching network coupled between an output of the amplifier arrangement and the first electrode, and a measurement and control system that can detect when a defrosting operation has completed. In an embodiment, the impedance matching network is a variable impedance matching network that can be adjusted during the defrosting operation to improve matching between the amplifier arrangement and the cavity.

Generally, the term "defrosting" means to elevate the temperature of a frozen load (e.g., a food load or other type of load) to a temperature at which the load is no longer frozen (e.g., a temperature at or near 0 degrees Celsius). As used herein, the term "defrosting" more broadly means a process by which the thermal energy or temperature of a load (e.g., a food load or other type of load) is increased through provision of RF power to the load. Accordingly, in various embodiments, a "defrosting operation" may be performed on a load with any initial temperature (e.g., any initial temperature above or below 0 degrees Celsius), and the defrosting operation may be ceased at any final temperature that is higher than the initial temperature (e.g., including final temperatures that are above or below 0 degrees Celsius). That said, the "defrosting operations" and "defrosting systems" described herein alternatively may be referred to as "thermal increase operations" and "thermal increase systems." The term "defrosting" should not be construed to limit application of the invention to methods or systems that are only capable of raising the temperature of a frozen load to a temperature at or near 0 degrees Celsius.

FIG. **1** is a perspective view of a defrosting system **100**, in accordance with an example embodiment. Defrosting system **100** includes a defrosting cavity **110**, a control panel **120**, one or more radio frequency (RF) signal sources (e.g., RF signal source **340**, FIG. **3**), a power supply (e.g., power supply **350**, FIG. **3**), a first electrode **170**, power detection circuitry (e.g., power detection circuitry **380**, FIG. **3**), and a system controller (e.g., system controller **330**, FIG. **3**). The defrosting cavity **110** is defined by interior surfaces of top, bottom, side, and back cavity walls **111**, **112**, **113**, **114**, **115** and an interior surface of door **116**. With door **116** closed, the defrosting cavity **110** defines an enclosed air cavity. As used herein, the term "air cavity" may mean an enclosed area that contains air or other gasses (e.g., defrosting cavity **110**).

According to an embodiment, the first electrode **170** is arranged proximate to a cavity wall (e.g., top wall **111**), the first electrode **170** is electrically isolated from the remaining cavity walls (e.g., walls **112-115** and door **116**), and the remaining cavity walls are grounded. In such a configuration, the system may be simplistically modeled as a capacitor, where the first electrode **170** functions as one conductive plate, the grounded cavity walls (e.g., walls **112-115**) function as a second conductive plate (or electrode), and the air cavity (including any load contained therein) function as a dielectric medium between the first and second conductive plates. Although not shown in FIG. **1**, a non-electrically conductive barrier (e.g., barrier **314**, FIG. **3**) also may be included in the system **100**, and the non-conductive barrier may function to electrically and physically isolate the load from the bottom cavity wall **112**. Although FIG. **1** shows the first electrode **170** being proximate to the top wall **111**, the first electrode **170** alternatively may be proximate to any of the other walls **112-115**, as indicated by alternate electrodes **172-175**.

According to an embodiment, during operation of the defrosting system **100**, a user (not illustrated) may place one or more loads (e.g., food and/or liquids) into the defrosting cavity **110**, and optionally may provide inputs via the control panel **120** that specify characteristics of the load(s). For example, the specified characteristics may include an approximate weight of the load. In addition, the specified load characteristics may indicate the material(s) from which the load is formed (e.g., meat, bread, liquid). In alternate embodiments, the load characteristics may be obtained in some other way, such as by scanning a barcode on the load packaging or receiving a radio frequency identification (RFID) signal from an RFID tag on or embedded within the load. Either way, as will be described in more detail later, information regarding such load characteristics enables the system controller (e.g., system controller **330**, FIG. **3**) to establish an initial state for the impedance matching network of the system at the beginning of the defrosting operation, where the initial state may be relatively close to an optimal state that enables maximum RF power transfer into the load. Alternatively, load characteristics may not be entered or received prior to commencement of a defrosting operation, and the system controller may establish a default initial state for the impedance matching network.

To begin the defrosting operation, the user may provide an input via the control panel **120**. In response, the system controller causes the RF signal source(s) (e.g., RF signal source **340**, FIG. **3**) to supply an RF signal to the first electrode **170**, which responsively radiates electromagnetic energy into the defrosting cavity **110**. The electromagnetic energy increases the thermal energy of the load (i.e., the electromagnetic energy causes the load to warm up).

During the defrosting operation, the impedance of the load (and thus the total input impedance of the cavity **110** plus load) changes as the thermal energy of the load increases. The impedance changes alter the absorption of RF energy into the load, and thus alter the magnitude of reflected power. According to an embodiment, power detection circuitry (e.g., power detection circuitry **380**, FIG. **3**) continuously or periodically measures the forward and reflected power along a transmission path (e.g., transmission path **348**, FIG. **3**) between the RF signal source (e.g., RF signal source **340**, FIG. **3**) and the first electrode **170**. Based on these measurements, the system controller (e.g., system controller **330**, FIG. **3**) may detect completion of the defrosting operation, as will be described in detail below. According to a further embodiment, the impedance matching network is variable, and based on the forward and reflected power measurements, the system controller may alter the state of the impedance matching network during the defrosting operation to increase the absorption of RF power by the load.

The defrosting system **100** of FIG. **1** is embodied as a counter-top type of appliance. In a further embodiment, the defrosting system **100** also may include components and functionality for performing microwave cooking operations. Alternatively, components of a defrosting system may be incorporated into other types of systems or appliances. For example, FIG. **2** is a perspective view of a refrigerator/freezer appliance **200** that includes other example embodiments of defrosting systems **210**, **220**. More specifically, defrosting system **210** is shown to be incorporated within a freezer compartment **212** of the system **200**, and defrosting system **220** is shown to be incorporated within a refrigerator compartment **222** of the system. An actual refrigerator/freezer appliance likely would include only one of the defrosting systems **210**, **220**, but both are shown in FIG. **2** to concisely convey both embodiments.

Similar to the defrosting system **100**, each of defrosting systems **210**, **220** includes a defrosting cavity, a control panel **214**, **224**, one or more RF signal sources (e.g., RF signal source **340**, FIG. **3**), a power supply (e.g., power supply **350**, FIG. **3**), a first electrode (e.g., electrode **370**, FIG. **3**), power detection circuitry (e.g., power detection circuitry **380**, FIG. **3**), and a system controller (e.g., system controller **330**, FIG. **3**). For example, the defrosting cavity may be defined by interior surfaces of bottom, side, front, and back walls of a drawer, and an interior top surface of a fixed shelf **216**, **226** under which the drawer slides. With the drawer slid fully under the shelf, the drawer and shelf define the cavity as an enclosed air cavity. The components and functionalities of the defrosting systems **210**, **220** may be substantially the same as the components and functionalities of defrosting system **100**, in various embodiments.

In addition, according to an embodiment, each of the defrosting systems **210**, **220** may have sufficient thermal communication with the freezer or refrigerator compartment **212**, **222**, respectively, in which the system **210**, **220** is disposed. In such an embodiment, after completion of a defrosting operation, the load may be maintained at a safe temperature (i.e., a temperature at which food spoilage is retarded) until the load is removed from the system **210**, **220**. More specifically, upon completion of a defrosting operation by the freezer-based defrosting system **210**, the cavity within which the defrosted load is contained may thermally communicate with the freezer compartment **212**, and if the load is not promptly removed from the cavity, the load may re-freeze. Similarly, upon completion of a defrosting operation by the refrigerator-based defrosting system **220**, the cavity within which the defrosted load is contained may thermally communicate with the refrigerator compartment **222**, and if the load is not promptly removed from the cavity, the load may be maintained in a defrosted state at the temperature within the refrigerator compartment **222**.

Those of skill in the art would understand, based on the description herein, that embodiments of defrosting systems may be incorporated into systems or appliances having other configurations, as well. Accordingly, the above-described implementations of defrosting systems in a stand-alone appliance, a microwave oven appliance, a freezer, and a refrigerator are not meant to limit use of the embodiments only to those types of systems.

Although defrosting systems **100**, **200** are shown with their components in particular relative orientations with respect to one another, it should be understood that the various components may be oriented differently, as well. In addition, the physical configurations of the various components may be different. For example, control panels **120**, **214**, **224** may have more, fewer, or different user interface elements, and/or the user interface elements may be differently arranged. In addition, although a substantially cubic defrosting cavity **110** is illustrated in FIG. **1**, it should be understood that a defrosting cavity may have a different shape, in other embodiments (e.g., cylindrical, and so on). Further, defrosting systems **100**, **210**, **220** may include additional components (e.g., a fan, a stationary or rotating plate, a tray, an electrical cord, and so on) that are not specifically depicted in FIGS. **1**, **2**.

FIG. **3** is a simplified block diagram of a defrosting system **300** (e.g., defrosting system **100**, **210**, **220**, FIGS. **1**, **2**), in accordance with an example embodiment. Defrosting system **300** includes defrosting cavity **310**, user interface **320**, system controller **330**, RF signal source **340**, power supply and bias circuitry **350**, variable impedance matching network **360**, electrode **370**, and power detection circuitry **380**, in an embodiment. In addition, in other embodiments, defrosting system **300** may include temperature sensor(s), infrared (IR) sensor(s), and/or weight sensor(s) **390**, although some or all of these sensor components may be excluded. It should be understood that FIG. **3** is a simplified representation of a defrosting system **300** for purposes of explanation and ease of description, and that practical embodiments may include other devices and components to provide additional functions and features, and/or the defrosting system **300** may be part of a larger electrical system.

User interface **320** may correspond to a control panel (e.g., control panel **120**, **214**, **224**, FIGS. **1**, **2**), for example, which enables a user to provide inputs to the system regarding parameters for a defrosting operation (e.g., characteristics of the load to be defrosted, and so on), start and cancel buttons, mechanical controls (e.g., a door/drawer open latch), and so on. In addition, the user interface may be configured to provide user-perceptible outputs indicating the status of a defrosting operation (e.g., a countdown timer, visible indicia indicating progress or completion of the defrosting operation, and/or audible tones indicating completion of the defrosting operation) and other information.

System controller **330** may include one or more general purpose or special purpose processors (e.g., a microprocessor, microcontroller, Application Specific Integrated Circuit (ASIC), and so on), volatile and/or non-volatile memory (e.g., Random Access Memory (RAM), Read Only Memory (ROM), flash, various registers, and so on), one or more communication busses, and other components. According to an embodiment, system controller **330** is coupled to user interface **320**, RF signal source **340**, variable impedance matching network **360**, power detection circuitry **380**, and sensors **390** (if included). System controller **330** is configured to receive signals indicating user inputs received via user interface **320**, and to receive forward and reflected power measurements from power detection circuitry **380**. Responsive to the received signals and measurements, and as will be described in more detail later, system controller **330** provides control signals to the power supply and bias circuitry **350** and to the RF signal generator **342** of the RF signal source **340**. In addition, system controller **330** provides control signals to the variable impedance matching network **360**, which cause the network **360** to change its state or configuration.

Defrosting cavity **310** includes a capacitive defrosting arrangement with first and second parallel plate electrodes that are separated by an air cavity within which a load **316** to be defrosted may be placed. For example, a first electrode **370** may be positioned above the air cavity, and a second electrode may be provided by a portion of a containment structure **312**. More specifically, the containment structure **312** may include bottom, top, and side walls, the interior surfaces of which define the cavity **310** (e.g., cavity **110**, FIG. **1**). According to an embodiment, the cavity **310** may be sealed (e.g., with a door **116**, FIG. **1** or by sliding a drawer closed under a shelf **216**, **226**, FIG. **2**) to contain the electromagnetic energy that is introduced into the cavity **310** during a defrosting operation. The system **300** may include one or more interlock mechanisms that ensure that the seal is intact during a defrosting operation. If one or more of the interlock mechanisms indicates that the seal is breached, the system controller **330** may cease the defrosting operation. According to an embodiment, the containment structure **312** is at least partially formed from conductive material, and the conductive portion(s) of the containment structure may be grounded. Alternatively, at least the portion of the containment structure **312** that corresponds to the bottom surface of the cavity **310** may be formed from conductive material and grounded. Either way, the containment structure **312** (or at least the portion of the containment structure **312** that is parallel with the first electrode **370**) functions as a second electrode of the capacitive defrosting arrangement. To avoid direct contact between the load **316** and the grounded bottom surface of the cavity **310**, a non-conductive barrier **314** may be positioned over the bottom surface of the cavity **310**.

Defrosting cavity **310** and any load **316** (e.g., food, liquids, and so on) positioned in the defrosting cavity **310** present a cumulative load for the electromagnetic energy (or RF power) that is radiated into the cavity **310** by the first electrode **370**. More specifically, the cavity **310** and the load **316** present an impedance to the system, referred to herein as a "cavity input impedance." The cavity input impedance changes during a defrosting operation as the temperature of the load **316** increases. As will be described in conjunction with FIGS. **10** and **11** later, the impedance of many types of food loads changes with respect to temperature in a somewhat predictable manner as the food load transitions from a frozen state to a defrosted state. According to an embodiment, based on reflected and forward power measurements from the power detection circuitry **380**, the system controller **330** is configured to identify a point in time during a defrosting operation when the rate of change of cavity input impedance indicates that the load **316** is approaching 0° Celsius, at which time the system controller **330** may terminate the defrosting operation.

The first electrode **370** is electrically coupled to the RF signal source **340** through a variable impedance matching network **360** and a transmission path **348**, in an embodiment. As will be described in more detail later, the variable impedance matching circuit **360** is configured to perform an impedance transformation from an impedance of the RF signal source **340** to an input impedance of defrosting cavity **340** as modified by the load **316**. In an embodiment, the variable impedance matching network **360** includes a network of passive components (e.g., inductors, capacitors, resistors). According to a more specific embodiment, the variable impedance matching network **360** includes a plurality of fixed-value lumped inductors (e.g., inductors **412-414**, **712-714**, **812-814**, FIGS. **4**, **7**, **8**) that are positioned within the cavity **310** and which are electrically coupled to the first electrode **370**. In addition, the variable impedance matching network **360** includes a plurality of variable inductance networks (e.g., networks **410**, **411**, **500**, FIGS. **4**, **5**), which may be located inside or outside of the cavity **310**. The inductance value provided by each of the variable inductance networks is established using control signals from the system controller **330**, as will be described in more detail later. In any event, by changing the state of the variable impedance matching network **360** over the course of a defrosting operation to dynamically match the ever-changing cavity input impedance, the amount of RF power that is absorbed by the load **316** may be maintained at a high level despite variations in the load impedance during the defrosting operation.

According to an embodiment, RF signal source **350** includes an RF signal generator **342** and a power amplifier (e.g., including one or more power amplifier stages **344**, **346**). In response to control signals provided by system controller **330**, RF signal generator **342** is configured to produce an oscillating electrical signal having a frequency in the ISM (industrial, scientific, and medical) band, although the system could be modified to support operations in other frequency bands, as well. The RF signal generator **342** may be controlled to produce oscillating signals of different power levels and/or different frequencies, in various embodiments. For example, the RF signal generator **342** may produce a signal that oscillates in a range of about 3.0 megahertz (MHz) to about 300 MHz. Some desirable frequencies may be, for example, 13.56 MHz (+/−5 percent), 27.125 MHz (+/−5 percent), and 40.68 MHz (+/−5 percent). In one particular embodiment, for example, the RF signal generator **342** may produce a signal that oscillates in a range of about 40.66 MHz to about 40.70 MHz and at a power level in a range of about 10 decibels (dB) to about 15 dB. Alternatively, the frequency of oscillation and/or the power level may be lower or higher than the above-given ranges or values.

In the embodiment of FIG. **3**, the power amplifier includes a driver amplifier stage **344** and a final amplifier stage **346**. The power amplifier is configured to receive the oscillating signal from the RF signal generator **342**, and to amplify the signal to produce a significantly higher-power signal at an output of the power amplifier. For example, the output signal may have a power level in a range of about 100 watts to about 400 watts or more. The gain applied by the power amplifier may be controlled using gate bias voltages and/or drain supply voltages provided by the power supply and bias circuitry **350** to each amplifier stage **344**, **346**. More specifically, power supply and bias circuitry **350** provides bias and supply voltages to each RF amplifier stage **344**, **346** in accordance with control signals received from system controller **330**.

In an embodiment, each amplifier stage **344**, **346** is implemented as a power transistor, such as a field effect transistor (FET), having an input terminal (e.g., a gate or control terminal) and two current carrying terminals (e.g., source and drain terminals). Impedance matching circuits (not illustrated) may be coupled to the input (e.g., gate) of the driver amplifier stage **344**, between the driver and final amplifier stages **346**, and/or to the output (e.g., drain terminal) of the final amplifier stage **346**, in various embodiments. In an embodiment, each transistor of the amplifier stages **344**, **346** includes a laterally diffused metal oxide semiconductor FET (LDMOSFET) transistor. However, it should be noted that the transistors are not intended to be limited to any particular semiconductor technology, and in other embodiments, each transistor may be realized as a gallium nitride (GaN) transistor, another type of MOSFET transistor, a bipolar junction transistor (BJT), or a transistor utilizing another semiconductor technology.

In FIG. **3**, the power amplifier arrangement is depicted to include two amplifier stages **344**, **346** coupled in a particular manner to other circuit components. In other embodiments, the power amplifier arrangement may include other amplifier topologies and/or the amplifier arrangement may include only one amplifier stage, or more than two amplifier stages. For example, the power amplifier arrangement may include various embodiments of a single ended amplifier, a double ended amplifier, a push-pull amplifier, a Doherty amplifier, a Switch Mode Power Amplifier (SMPA), or another type of amplifier.

Power detection circuitry **380** is coupled along the transmission path **348** between the output of the RF signal source **340** and the input to the variable impedance matching network **360**, in an embodiment. In an alternate embodiment, power detection circuitry **380** may be coupled to the transmission path **349** between the output of the variable impedance matching network **360** and the first electrode **370**. Either way, power detection circuitry **380** is configured to monitor, measure, or otherwise detect the power of the forward signals (i.e., from RF signal source **340** toward first electrode **370**) and the reflected signals (i.e., from first electrode **370** toward RF signal source **340**) traveling along the transmission path **348**.

Power detection circuitry **380** supplies signals conveying the magnitudes of the forward and reflected signal power to system controller **330**. System controller **330**, in turn, may calculate a ratio of reflected signal power to forward signal power, or the S11 parameter. As will be described in more detail below, when the reflected to forward power ratio exceeds a threshold, this indicates that the system **300** is not adequately matched, and that energy absorption by the load **316** may be sub-optimal. In such a situation, system controller **330** orchestrates a process of altering the state of the variable impedance matching network until the reflected to forward power ratio decreases to a desired level, thus re-establishing an acceptable match and facilitating more optimal energy absorption by the load **316**.

As mentioned above, some embodiments of defrosting system **300** may include temperature sensor(s), IR sensor(s), and/or weight sensor(s) **390**. The temperature sensor(s) and/or IR sensor(s) may be positioned in locations that enable the temperature of the load **316** to be sensed during the defrosting operation. When provided to the system controller **330**, the temperature information enables the system controller **330** to alter the power of the RF signal supplied by the RF signal source **340** (e.g., by controlling the bias and/or supply voltages provided by the power supply and bias circuitry **350**), to adjust the state of the variable impedance matching network **360**, and/or to determine when the defrosting operation should be terminated. The weight sensor(s) are positioned under the load **316**, and are configured to provide an estimate of the weight of the load **316** to the system controller **330**. The system controller **330** may use this information, for example, to determine a desired power level for the RF signal supplied by the RF signal source **340**, to determine an initial setting for the variable impedance matching network **360**, and/or to determine an approximate duration for the defrosting operation.

As discussed above, the variable impedance matching network **360** is used to match the input impedance of the defrosting cavity **310** plus load **316** to maximize, to the extent possible, the RF power transfer into the load **316**. The initial impedance of the defrosting cavity **310** and the load **316** may not be known with accuracy at the beginning of a defrosting operation. Further, the impedance of the load **316** changes during a defrosting operation as the load **316** warms up. According to an embodiment, the system controller **330** may provide control signals to the variable impedance matching network **360**, which cause modifications to the state of the variable impedance matching network **360**. This enables the system controller **330** to establish an initial state of the variable impedance matching network **360** at the beginning of the defrosting operation that has a relatively low reflected to forward power ratio, and thus a relatively high absorption of the RF power by the load **316**. In addition, this enables the system controller **330** to modify the state of the variable impedance matching network **360** so that an adequate match may be maintained throughout the defrosting operation, despite changes in the impedance of the load **316**.

According to an embodiment, the variable impedance matching network **360** may include a network of passive components, and more specifically a network of fixed-value inductors (e.g., lumped inductive components) and variable inductors (or variable inductance networks). As used herein, the term "inductor" means a discrete inductor or a set of inductive components that are electrically coupled together without intervening components of other types (e.g., resistors or capacitors).

FIG. **4** is a schematic diagram of a variable impedance matching network **400** (e.g., variable impedance matching network **360**, FIG. **3**), in accordance with an example embodiment. As will be explained in more detail below, the variable impedance matching network **360** essentially has two portions: one portion to match the RF signal source (or the final stage power amplifier); and another portion to match the cavity plus load.

Variable impedance matching network **400** includes an input node **402**, an output node **404**, first and second variable inductance networks **410**, **411**, and a plurality of fixed-value inductors **412**-**415**, according to an embodiment. When incorporated into a defrosting system (e.g., system **300**, FIG. **3**), the input node **402** is electrically coupled to an output of the RF signal source (e.g., RF signal source **340**, FIG. **3**), and the output node **404** is electrically coupled to an electrode (e.g., first electrode **370**, FIG. **3**) within the defrosting cavity (e.g., defrosting cavity **310**, FIG. **3**).

Between the input and output nodes **402**, **404**, the variable impedance matching network **400** includes first and second, series coupled lumped inductors **412**, **414**, in an embodiment. The first and second lumped inductors **412**, **414** are relatively large in both size and inductance value, in an embodiment, as they may be designed for relatively low frequency (e.g., about 4.66 MHz to about 4.68 MHz) and high power (e.g., about 50 watts (W) to about 500 W) operation. For example, inductors **412**, **414** may have values in a range of about 200 nanohenries (nH) to about 600 nH, although their values may be lower and/or higher, in other embodiments.

The first variable inductance network **410** is a first shunt inductive network that is coupled between the input node **402** and a ground reference terminal (e.g., the grounded containment structure **312**, FIG. **3**). According to an embodiment, the first variable inductance network **410** is configurable to match the impedance of the RF signal source (e.g., RF signal source **340**, FIG. **3**), or more particularly to match the final stage power amplifier (e.g., amplifier **346**, FIG. **3**). Accordingly, the first variable inductance network **410** may be referred to as the "power amplifier matching portion" of the variable impedance matching network **400**. According to an embodiment, and as will be described in more detail in conjunction with FIG. **5**, the first variable inductance network **410** includes a network of inductive components that may be selectively coupled together to provide inductances in a range of about 20 nH to about 400 nH, although the range may extend to lower or higher inductance values, as well.

In contrast, the "cavity matching portion" of the variable impedance matching network **400** is provided by a second shunt inductive network **416** that is coupled between a node **422** between the first and second lumped inductors **412**, **414** and the ground reference terminal. According to an embodiment, the second shunt inductive network **416** includes a third lumped inductor **413** and a second variable inductance network **411** coupled in series, with an intermediate node **422** between the third lumped inductor **413** and the second variable inductance network **411**. Because the state of the second variable inductance network **411** may be changed to provide multiple inductance values, the second shunt inductive network **416** is configurable to optimally match the impedance of the cavity plus load (e.g., cavity **310** plus load **316**, FIG. **3**). For example, inductor **413** may have a value in a range of about 400 nH to about 800 nH, although its value may be lower and/or higher, in other embodiments. According to an embodiment, and as will be described in more detail in conjunction with FIG. **5**, the second variable inductance network **411** includes a network of inductive components that may be selectively coupled together to provide inductances in a range of about 50 nH to about 800 nH, although the range may extend to lower or higher inductance values, as well.

Finally, the variable impedance matching network **400** includes a fourth lumped inductor **415** coupled between the output node **404** and the ground reference terminal. For example, inductor **415** may have a value in a range of about 400 nH to about 800 nH, although its value may be lower and/or higher, in other embodiments.

As will be described in more detail in conjunction with FIGS. **7** and **8**, the set **430** of lumped inductors **412**-**415** may be physically located within the cavity (e.g., cavity **310**, FIG. **3**), or at least within the confines of the containment structure (e.g., containment structure **312**, FIG. **3**). This enables the radiation produced by the lumped inductors **412**-**415** to be safely contained within the system, rather than being radiated out into the surrounding environment. In contrast, the variable inductance networks **410**, **411** may or may not be contained within the cavity or the containment structure, in various embodiments.

According to an embodiment, the variable impedance matching network **400** embodiment of FIG. **4** includes "only inductors" to provide a match for the input impedance of the defrosting cavity **310** plus load **316**. Thus, the network **400** may be considered an "inductor-only" matching network. As used herein, the phrases "only inductors" or "inductor-only" when describing the components of the variable impedance matching network means that the network does not include discrete resistors with significant resistance values or discrete capacitors with significant capacitance values. In some cases, conductive transmission lines between components of the matching network may have minimal resistances, and/or minimal parasitic capacitances may be present within the network. Such minimal resistances and/or minimal parasitic capacitances are not to be construed as converting embodiments of the "inductor-only" network into a matching network that also includes resistors and/or capacitors. Those of skill in the art would understand, however, that other embodiments of variable impedance matching networks may include differently configured inductor-only matching networks, and matching networks that include combinations of discrete inductors, discrete capacitors, and/or discrete resistors. As will be described in more detail in conjunction with FIG. **6**, an "inductor-only" matching network alternatively may be defined as a matching network that enables impedance matching of a capacitive load using solely or primarily inductive components.

FIG. **5** is a schematic diagram of a variable inductance network **500** that may be incorporated into a variable impedance matching network (e.g., as variable inductance networks **410** and/or **411**, FIG. **4**), in accordance with an example embodiment. Network **500** includes an input node **530**, an output node **532**, and a plurality, N, of discrete inductors **501-504** coupled in series with each other between the input and output nodes **530**, **523**, where N may be an integer between 2 and 10, or more. In addition, network **500** includes a plurality, N, of switches **511-514**, where each switch **511-514** is coupled in parallel across the terminals of one of the inductors **501-504**. Switches **511-514** may be implemented as transistors, mechanical relays or mechanical switches, for example. The electrically conductive state of each switch **511-514** (i.e., open or closed) is controlled using control signals **521-524** from the system controller (e.g., system controller **330**, FIG. **3**).

For each parallel inductor/switch combination, substantially all current flows through the inductor when its corresponding switch is in an open or non-conductive state, and substantially all current flows through the switch when the switch is in a closed or conductive state. For example, when all switches **511-514** are open, as illustrated in FIG. **5**, substantially all current flowing between input and output nodes **530**, **532** flows through the series of inductors **501-504**. This configuration represents the maximum inductance state of the network **500** (i.e., the state of network **500** in which a maximum inductance value is present between input and output nodes **530**, **532**). Conversely, when all switches **511-514** are closed, substantially all current flowing between input and output nodes **530**, **532** bypasses the inductors **501-504** and flows instead through the switches **511-514** and the conductive interconnections between nodes **530**, **532** and switches **511-514**. This configuration represents the minimum inductance state of the network **500** (i.e., the state of network **500** in which a minimum inductance value is present between input and output nodes **530**, **532**). Ideally, the minimum inductance value would be near zero inductance. However, in practice a "trace" inductance is present in the minimum inductance state due to the cumulative inductances of the switches **511-514** and the conductive interconnections between nodes **530**, **532** and the switches **511-514**. For example, in the minimum inductance state, the trace inductance for the variable inductance network **500** may be in a range of about 20 nH to about 50 nH, although the trace inductance may be smaller or larger, as well. Larger, smaller, or substantially similar trace inductances also may be inherent in each of the other network states, as well, where the trace inductance for any given network state is a summation of the inductances of the sequence of conductors and switches through which the current primarily is carried through the network **500**.

Starting from the maximum inductance state in which all switches **511-514** are open, the system controller may provide control signals **521-524** that result in the closure of any combination of switches **511-514** in order to reduce the inductance of the network **500** by bypassing corresponding combinations of inductors **501-504**. In one embodiment, each inductor **501-504** has substantially the same inductance value, referred to herein as a normalized value of 1. For example, each inductor **501-504** may have a value in a range of about 100 nH to about 200 nH, or some other value. In such an embodiment, the maximum inductance value for the network **500** (i.e., when all switches **511-514** are in an open state) would be about N×I, plus any trace inductance that may be present in the network **500** when it is in the maximum inductance state. When any n switches are in a closed state, the inductance value for the network **500** would be about (N−n)×I (plus trace inductance). In such an embodiment, the state of the network **500** may be configured to have any of N+1 values of inductance.

In an alternate embodiment, the inductors **501-504** may have different values from each other. For example, moving from the input node **530** toward the output node **532**, the first inductor **501** may have a normalized inductance value of I, and each subsequent inductor **502-504** in the series may have a larger or smaller inductance value. For example, each subsequent inductor **502-504** may have an inductance value that is a multiple (e.g., about twice) the inductance value of the nearest downstream inductor **501-503**, although the difference may not necessarily be an integer multiple. In such an embodiment, the state of the network **500** may be configured to have any of 2^N values of inductance. For example, when N=4 and each inductor **501-504** has a different value, the network **500** may be configured to have any of 16 values of inductance. For example but not by way of limitation, assuming that inductor **501** has a value of I, inductor **502** has a value of 2×I, inductor **503** has a value of 4×I, and inductor **504** has a value of 8×I, Table 1, below indicates the total inductance value for all 16 possible states of the network **500** (not accounting for trace inductances):

TABLE 1

Total inductance values for all possible variable inductance network states

Network state	Switch 511 state (501 value = I)	Switch 512 state (502 value = 2 × I)	Switch 513 state (503 value = 4 × I)	Switch 514 state (504 value = 8 × I)	Total network inductance (w/o trace inductance)
0	closed	closed	closed	closed	0
1	open	closed	closed	closed	I
2	closed	open	closed	closed	2 × I
3	open	open	closed	closed	3 × I
4	closed	closed	open	closed	4 × I
5	open	closed	open	closed	5 × I
6	closed	open	open	closed	6 × I
7	open	open	open	closed	7 × I
8	closed	closed	closed	open	8 × I
9	open	closed	closed	open	9 × I
10	closed	open	closed	open	10 × I
11	open	open	closed	open	11 × I
12	closed	closed	open	open	12 × I
13	open	closed	open	open	13 × I
14	closed	open	open	open	14 × I
15	open	open	open	open	15 × I

Referring again to FIG. **4**, an embodiment of variable inductance network **410** may be implemented in the form of variable inductance network **500** with the above-described example characteristics (i.e., N=4 and each successive inductor is about twice the inductance of the preceding inductor). Assuming that the trace inductance in the minimum inductance state is about 20 nH, and the range of inductance values achievable by network **410** is about 20 nH (trace inductance) to about 400 nH, the values of inductors **501-504** may be, for example, about 30 nH, about 50 nH, about 100 nH, and about 200 nH, respectively. Similarly, if an embodiment of variable inductance network **411** is implemented in the same manner, and assuming that the trace inductance is about 50 nH and the range of inductance values achievable by network **411** is about 50 nH (trace inductance) to about 800 nH, the values of inductors **501-504** may be, for example, about 50 nH, about 100 nH, about 200 nH, and about 400 nH, respectively. Of course, more or fewer than four inductors **501-504** may be included in either variable inductance network **410**, **411**, and the inductors within each network **410**, **411** may have different values.

Although the above example embodiment specifies that the number of switched inductances in the network **500** equals four, and that each inductor **501-504** has a value that is some multiple of a value of I, alternate embodiments of variable inductance networks may have more or fewer than four inductors, different relative values for the inductors, a different number of possible network states, and/or a different configuration of inductors (e.g., differently connected sets of parallel and/or series coupled inductors). Either way, by providing a variable inductance network in an impedance matching network of a defrosting system, the system may be better able to match the ever-changing cavity input impedance that is present during a defrosting operation.

FIG. **6** is an example of a Smith chart **600** depicting how the plurality of inductances in an embodiment of a variable impedance matching network (e.g., network **360**, **400**, FIGS. **3**, **4**) may match the input cavity impedance to the RF signal source. The example Smith chart **600** assumes that the system is a 50 Ohm system, and that the output of the RF signal source is 50 Ohms. Those of skill in the art would understand, based on the description herein, how the Smith chart could be modified for a system and/or RF signal source with different characteristic impedances.

In Smith chart **600**, point **601** corresponds to the point at which the load (e.g., the cavity **310** plus load **316**, FIG. **3**) would locate (e.g., at the beginning of a defrosting operation) absent the matching provided by the variable impedance matching network (e.g., network **360**, **400**, FIGS. **3**, **4**). As indicated by the position of the load point **601** in the lower right quadrant of the Smith chart **600**, the load is a capacitive load. According to an embodiment, the shunt and series inductances of the variable impedance matching network sequentially move the substantially-capacitive load impedance toward an optimal matching point **606** (e.g., 50 Ohms) at which RF energy transfer to the load may occur with minimal losses. More specifically, and referring also to FIG. **4**, shunt inductance **415** moves the impedance to point **602**, series inductance **414** moves the impedance to point **603**, shunt inductance **416** moves the impedance to point **604**, series inductance **412** moves the impedance to point **605**, and shunt inductance **410** moves the impedance to the optimal matching point **606**.

It should be noted that the combination of impedance transformations provided by embodiments of the variable impedance matching network keep the impedance at any point within or very close to the lower right quadrant of the Smith chart **600**. As this quadrant of the Smith chart **600** is characterized by relatively high impedances and relatively low currents, the impedance transformation is achieved without exposing components of the circuit to relatively high and potentially damaging currents. Accordingly, an alternate definition of an "inductor-only" matching network, as used herein, may be a matching network that enables impedance matching of a capacitive load using solely or primarily inductive components, where the impedance matching network performs the transformation substantially within the lower right quadrant of the Smith chart.

As discussed previously, the impedance of the load changes during the defrosting operation. Accordingly, point **601** correspondingly moves during the defrosting operation. Movement of load point **601** is compensated for, according to the previously-described embodiments, by varying the impedance of the first and second shunt inductances **410**, **411** so that the final match provided by the variable impedance matching network still may arrive at or near the optimal matching point **606**. Although a specific variable impedance matching network has been illustrated and described herein, those of skill in the art would understand, based on the description herein, that differently-configured variable impedance matching networks may achieve the same or similar results to those conveyed by Smith chart **600**. For example, alternative embodiments of a variable impedance matching network may have more or fewer shunt and/or series inductances, and or different ones of the inductances may be configured as variable inductance networks (e.g., including one or more of the series inductances). Accordingly, although a particular variable inductance matching network has been illustrated and described herein, the inventive subject matter is not limited to the illustrated and described embodiment.

A particular physical configuration of a defrosting system will now be described in conjunction with FIGS. **7** and **8**. More particularly, FIG. **7** is a cross-sectional, side view of a defrosting system **700**, in accordance with an example embodiment, and FIG. **8** is a perspective view of a portion of defrosting system **700**. The defrosting system **700** generally includes a defrosting cavity **774**, a user interface (not shown), a system controller **730**, an RF signal source **740**, power supply and bias circuitry (not shown), power detection circuitry **780**, a variable impedance matching network **760**, a first electrode **770**, and a second electrode **772**, in an embodiment. In addition, in some embodiments, defrosting system **700** may include weight sensor(s) **790**, temperature sensor(s), and/or IR sensor(s) **792**.

The defrosting system **700** is contained within a containment structure **750**, in an embodiment. According to an embodiment, the containment structure **750** may define three interior areas: the defrosting cavity **774**, a fixed inductor area **776**, and a circuit housing area **778**. The containment structure **750** includes bottom, top, and side walls. Portions of the interior surfaces of some of the walls of the containment structure **750** may define the defrosting cavity **774**. The defrosting cavity **774** includes a capacitive defrosting arrangement with first and second parallel plate electrodes **770**, **772** that are separated by an air cavity within which a load **716** to be defrosted may be placed. For example, the first electrode **770** may be positioned above the air cavity, and a second electrode **772** may be provided by a conductive portion of the containment structure **750** (e.g., a portion of the bottom wall of the containment structure **750**). Alternatively, the second electrode **772** may be formed from a conductive plate that is distinct from the containment structure **750**. According to an embodiment, non-electrically conductive support structure(s) **754** may be employed to suspend the first electrode **770** above the air cavity, to electrically isolate the first electrode **770** from the containment structure **750**, and to hold the first electrode **770** in a fixed physical orientation with respect to the air cavity.

According to an embodiment, the containment structure **750** is at least partially formed from conductive material, and the conductive portion(s) of the containment structure may be grounded to provide a ground reference for various electrical components of the system. Alternatively, at least the portion of the containment structure **750** that corresponds to the second electrode **772** may be formed from conductive material and grounded. To avoid direct contact between the load **716** and the second electrode **772**, a non-conductive barrier **756** may be positioned over the second electrode **772**.

When included in the system **700**, the weight sensor(s) **790** are positioned under the load **716**. The weight sensor(s) **790** are configured to provide an estimate of the weight of the load **716** to the system controller **730**. The temperature sensor(s) and/or IR sensor(s) **792** may be positioned in locations that enable the temperature of the load **716** to be sensed both before, during, and after a defrosting operation. According to an embodiment, the temperature sensor(s) and/or IR sensor(s) **792** are configured to provide load temperature estimates to the system controller **730**.

Some or all of the various components of the system controller **730**, the RF signal source **740**, the power supply and bias circuitry (not shown), the power detection circuitry **780**, and portions **710**, **711** of the variable impedance matching network **760**, may be coupled to a common substrate **752** within the circuit housing area **778** of the containment structure **750**, in an embodiment. According to an embodiment, the system controller **730** is coupled to the user interface, RF signal source **740**, variable impedance matching network **760**, and power detection circuitry **780** through various conductive interconnects on or within the common substrate **752**. In addition, the power detection circuitry **780** is coupled along the transmission path **748** between the output of the RF signal source **740** and the input **702** to the variable impedance matching network **760**, in an embodiment. For example, the substrate **752** may include a microwave or RF laminate, a polytetrafluorethylene (PTFE) substrate, a printed circuit board (PCB) material substrate (e.g., FR-4), an alumina substrate, a ceramic tile, or another type of substrate. In various alternate embodiments, various ones of the components may be coupled to different substrates with electrical interconnections between the substrates and components. In still other alternate embodiments, some or all of the components may be coupled to a cavity wall, rather than being coupled to a distinct substrate.

The first electrode **770** is electrically coupled to the RF signal source **740** through a variable impedance matching network **760** and a transmission path **748**, in an embodiment. As discussed previously, the variable impedance matching network **760** includes variable inductance networks **710**, **711** (e.g., networks **410**, **411**, FIG. **4**) and a plurality of fixed-value lumped inductors **712**-**715** (e.g., inductors **412**-**415**, FIG. **4**). In an embodiment, the variable inductance networks **710**, **711** are coupled to the common substrate **752** and located within the circuit housing area **778**. In contrast, the fixed-value lumped inductors **712**-**715** are positioned within the fixed inductor area **776** of the containment structure **750** (e.g., between the common substrate **752** and the first electrode **770**). Conductive structures (e.g., conductive vias or other structures) may provide for electrical communication between the circuitry within the circuit housing area **778** and the lumped inductors **712**-**715** within the fixed inductor area **776**.

For enhanced understanding of the system **700**, the nodes and components of the variable impedance matching network **760** depicted in FIGS. **7** and **8** will now be correlated with nodes and components of the variable impedance matching network **400** depicted in FIG. **4**. More specifically, the variable impedance matching network **760** includes an input node **702** (e.g., input node **402**, FIG. **4**), an output node **704** (e.g., output node **404**, FIG. **4**), first and second variable inductance networks **710**, **711** (e.g., variable inductance networks **410**, **411**, FIG. **4**), and a plurality of fixed-value inductors **712**-**715** (e.g., inductors **412**-**415**, FIG. **4**), according to an embodiment. The input node **702** is electrically coupled to an output of the RF signal source **740** through various conductive structures (e.g., conductive vias and traces), and the output node **704** is electrically coupled to the first electrode **770**.

Between the input and output nodes **702**, **704** (e.g., input and output nodes **402**, **404**, FIG. **4**), the variable impedance matching network **700** includes four lumped inductors **712**-**715** (e.g., inductors **412**-**415**, FIG. **4**), in an embodiment, which are positioned within the fixed inductor area **776**. An enhanced understanding of an embodiment of a physical configuration of the lumped inductors **712**-**715** within the fixed inductor area **776** may be achieved by referring to both FIG. **7** and to FIG. **8** simultaneously, where FIG. **8** depicts a top perspective view of the fixed inductor area **776**. In FIG. **8**, the irregularly shaped, shaded areas underlying inductors **712**-**715** represents suspension of the inductors **712**-**715** in space over the first electrode **770**. In other words, the shaded areas indicate where the inductors **712**-**715** are electrically insulated from the first electrode **770** by air. Rather than relying on an air dielectric, non-electrically conductive spacers may be included in these areas.

In an embodiment, the first lumped inductor **712** has a first terminal that is electrically coupled to the input node **702** (and thus to the output of RF signal source **740**), and a second terminal that is electrically coupled to a first intermediate node **720** (e.g., node **420**, FIG. **4**). The second lumped inductor **713** has a first terminal that is electrically coupled to the first intermediate node **720**, and a second terminal that is electrically coupled to a second intermediate node **722** (e.g., node **422**, FIG. **4**). The third lumped inductor **714** has a first terminal that is electrically coupled to the first intermediate node **720**, and a second terminal that is electrically coupled to the output node **704** (and thus to the first electrode **770**). The fourth lumped inductor **715** has a first terminal that is electrically coupled to the output node **704** (and thus to the first electrode **770**), and a second terminal that is electrically coupled to a ground reference node (e.g., to the grounded containment structure **750** through one or more conductive interconnects).

The first variable inductance network **710** (e.g., network **410**, FIG. **4**) is electrically coupled between the input node **702** and a ground reference terminal (e.g., the grounded containment structure **750**). Finally, the second shunt inductive network **716** is electrically coupled between the second intermediate node **722** and the ground reference terminal.

Now that embodiments of the electrical and physical aspects of defrosting systems have been described, various embodiments of methods for operating such defrosting systems will now be described in conjunction with FIGS. **9**-**12**. More specifically, FIG. **9** is a flowchart of a method of operating a defrosting system (e.g., system **100**, **210**, **220**, **300**, **700**, FIGS. **1**-**3**, **7**) with dynamic load matching, in accordance with an example embodiment.

The method may begin, in block **902**, when the system controller (e.g., system controller **330**, FIG. **3**) receives an indication that a defrosting operation should start. Such an indication may be received, for example, after a user has place a load (e.g., load **316**, FIG. **3**) into the system's defrosting cavity (e.g., cavity **310**, FIG. **3**), has sealed the cavity (e.g., by closing a door or drawer), and has pressed a start button (e.g., of the user interface **320**, FIG. **3**). In an embodiment, sealing of the cavity may engage one or more safety interlock mechanisms, which when engaged, indicate that RF power supplied to the cavity will not substantially leak into the environment outside of the cavity. As will be described later, disengagement of a safety interlock mechanism may cause the system controller immediately to pause or terminate the defrosting operation.

According to various embodiments, the system controller optionally may receive additional inputs indicating the load type (e.g., meats, liquids, or other materials), the initial load temperature, and/or the load weight. For example, information regarding the load type may be received from the user through interaction with the user interface (e.g., by the user selecting from a list of recognized load types). Alternatively, the system may be configured to scan a barcode visible on the exterior of the load, or to receive an electronic signal from an RFID device on or embedded within the load. Information regarding the initial load temperature may be received, for example, from one or more temperature sensors and/or IR sensors (e.g., sensors **390**, **792**, FIGS. **3**, **7**) of the system. Information regarding the load weight may be received from the user through interaction with the user interface, or from a weight sensor (e.g., sensor **390**, **790**, FIGS. **3**, **7**) of the system. As indicated above, receipt of inputs indicating the load type, initial load temperature, and/or load weight is optional, and the system alternatively may not receive some or all of these inputs.

In block **904**, the system controller provides control signals to the variable matching network (e.g., network **360**, **400**, FIGS. **3**, **4**) to establish an initial configuration or state for the variable matching network. As described in detail in conjunction with FIGS. **4** and **5**, the control signals affect the inductances of variable inductance networks (e.g., networks **410**, **411**, FIG. **4**) within the variable matching network. For example, the control signals may affect the states of bypass switches (e.g., switches **511**-**514**, FIG. **5**), which are responsive to the control signals from the system controller (e.g., control signals **521**-**524**, FIG. **5**).

As also discussed previously, a first portion of the variable matching network may be configured to provide a match for the RF signal source (e.g., RF signal source **340**, FIG. **3**) or the final stage power amplifier (e.g., power amplifier **346**, FIG. **3**), and a second portion of the variable matching network may be configured to provide a match for the cavity (e.g., cavity **310**, FIG. **3**) plus the load (e.g., load **316**, FIG. **3**). For example, referring to FIG. **4**, a first shunt, variable inductance network **410** may be configured to provide the RF signal source match, and a second shunt, variable inductance network **416** may be configured to provide the cavity plus load match.

It has been observed that a best initial overall match for a frozen load (i.e., a match at which a maximum amount of RF power is absorbed by the load) typically has a relatively high inductance for the cavity matching portion of the matching network, and a relatively low inductance for the RF signal source matching portion of the matching network. For example, FIG. **10** is a chart plotting optimal cavity match setting versus RF signal source match setting through a defrost operation for two different loads, where trace **1010** corresponds to a first load (e.g., having a first type, weight, and so on), and trace **1020** corresponds to a second load (e.g., having a second type, weight, and so on). In FIG. **10**, the optimal initial match settings for the two loads at the beginning of a defrost operation (e.g., when the loads are frozen) are indicated by points **1012** and **1022**, respectively. As can be seen, both points **1012** and **1022** indicate relatively high cavity match settings in comparison to relatively low RF source match settings. Referring to the embodiment of FIG. **4**, this translates to a relatively high inductance for variable inductance network **416**, and a relatively low inductance for variable inductance network **410**.

According to an embodiment, to establish the initial configuration or state for the variable matching network in block **904**, the system controller sends control signals to the first and second variable inductance networks (e.g., networks **410**, **411**, FIG. **4**) to cause the variable inductance network for the RF signal source match (e.g., network **410**) to have a relatively low inductance, and to cause the variable inductance network for the cavity match (e.g., network **411**) to have a relatively high inductance. The system controller may determine how low or how high the inductances are set based on load type/weight/temperature information known to the system controller a priori. If no a priori load type/weight/temperature information is available to the system controller, the system controller may select a relatively low default inductance for the RF signal source match and a relatively high default inductance for the cavity match.

Assuming, however, that the system controller does have a priori information regarding the load characteristics, the system controller may attempt to establish an initial configuration near the optimal initial matching point. For example, and referring again to FIG. **10**, the optimal initial matching point **1012** for the first type of load has a cavity match (e.g., implemented by network **411**) of about 80 percent of the network's maximum value, and has an RF signal source match (e.g., implemented by network **410**) of about 10 percent of the network's maximum value. Assuming each of the variable inductance networks has a structure similar to the network **500** of FIG. **5**, for example, and assuming that the states from Table 1, above, apply, then for the first type of load, system controller may initialize the variable inductance network so that the cavity match network (e.g., network **411**) has state 12 (i.e., about 80 percent of the maximum possible inductance of network **411**), and the RF signal source match network (e.g., network **410**) has state 2 (i.e., about 10 percent of the maximum possible inductance of network **410**). Conversely, the optimal initial matching point **1022** for the second type of load has a cavity match (e.g., implemented by network **411**) of about 40 percent of the network's maximum value, and has an RF signal source match (e.g., implemented by network **410**) of about 10 percent of the network's maximum value. Accordingly, for the second type of load, system controller may initialize the variable inductance network so that the cavity match network (e.g., network **411**) has state 6 (i.e., about 40 percent of the maximum possible inductance of network **411**), and the RF signal source match network (e.g., network **410**) has state 2 (i.e., about 10 percent of the maximum possible inductance of network **410**).

Referring again to FIG. **9**, once the initial variable matching network configuration is established, the system controller may perform a process **910** of adjusting, if necessary, the configuration of the variable impedance matching network to find an acceptable or best match based on actual measurements that are indicative of the quality of the match. According to an embodiment, this process includes causing the RF signal source (e.g., RF signal source **340**) to supply a relatively low power RF signal through the variable impedance matching network to the first electrode (e.g., first electrode **370**), in block **912**. The system controller may control the RF signal power level through control signals to the power supply and bias circuitry (e.g., circuitry **350**, FIG. **3**), where the control signals cause the power supply and bias circuitry to provide supply and bias voltages to the amplifiers (e.g., amplifier stages **344**, **346**, FIG. **3**) that are consistent with the desired signal power level. For example, the relatively low power RF signal may be a signal having a power level in a range of about 10 W to about 20 W, although different power levels alternatively may be used. A relatively low power level signal during the match adjustment process **910** is desirable to reduce the risk of damaging the cavity or load (e.g., if the initial match causes high reflected power), and to reduce the risk of damaging the switching components of the variable inductance networks (e.g., due to arcing across the switch contacts).

In block **914**, power detection circuitry (e.g., power detection circuitry **380**, FIG. **3**) then measures the forward and reflected power along the transmission path (e.g., path **348**, FIG. **3**) between the RF signal source and the first electrode, and provides those measurements to the system controller. The system controller may then determine a ratio between the reflected and forward signal powers, and may determine the S11 parameter for the system based on the ratio. The system controller may store the calculated ratios and/or S11 parameters for future evaluation or comparison, in an embodiment.

In block **916**, the system controller may determine, based on the reflected-to-forward signal power ratio and/or the S11 parameter, whether or not the match provided by the variable impedance matching network is acceptable (e.g., the ratio is 10 percent or less, or compares favorably with some other criteria). Alternatively, the system controller may be configured to determine whether the match is the "best" match. A "best" match may be determined, for example, by iteratively measuring the forward and reflected RF power for all possible impedance matching network configurations (or at least for a defined subset of impedance matching network configurations), and determining which configuration results in the lowest reflected-to-forward power ratio.

When the system controller determines that the match is not acceptable or is not the best match, the system controller may adjust the match, in block **918**, by reconfiguring the variable inductance matching network. For example, this may be achieved by sending control signals to the variable impedance matching network, which cause the network to increase and/or decrease the variable inductances within the network (e.g., by causing the variable inductance networks **410**, **411** to have different inductance states). After reconfiguring the variable inductance network, blocks **914**, **916**, and **918** may be iteratively performed until an acceptable or best match is determined in block **916**.

Once an acceptable or best match is determined, the defrosting operation may commence. Commencement of the defrosting operation includes increasing the power of the RF signal supplied by the RF signal source (e.g., RF signal source **340**) to a relatively high power RF signal, in block **920**. Once again, the system controller may control the RF signal power level through control signals to the power supply and bias circuitry (e.g., circuitry **350**, FIG. **3**), where the control signals cause the power supply and bias circuitry to provide supply and bias voltages to the amplifiers (e.g., amplifier stages **344**, **346**, FIG. **3**) that are consistent with the desired signal power level. For example, the relatively high power RF signal may be a signal having a power level in a range of about 50 W to about 500 W, although different power levels alternatively may be used.

In block **922**, power detection circuitry (e.g., power detection circuitry **380**, FIG. **3**) then periodically measures the forward and reflected power along the transmission path (e.g., path **348**, FIG. **3**) between the RF signal source and the first electrode, and provides those measurements to the system controller. The system controller again may determine a ratio between the reflected and forward signal powers, and may determine the S11 parameter for the system based on the ratio. The system controller may store the calculated ratios and/or S11 parameters for future evaluation or comparison, in an embodiment. According to an embodiment, the periodic measurements of the forward and reflected power may be taken at a fairly high frequency (e.g., on the order of milliseconds) or at a fairly low frequency (e.g., on the order of seconds). For example, a fairly low frequency for taking the periodic measurements may be a rate of one measurement every 10 seconds to 20 seconds.

In block **924**, the system controller may determine, based on one or more calculated reflected-to-forward signal power ratios and/or one or more calculated S11 parameters, whether or not the match provided by the variable impedance matching network is acceptable. For example, the system controller may use a single calculated reflected-to-forward signal power ratio or S11 parameter in making this determination, or may take an average (or other calculation) of a number of previously-calculated reflected-to-forward power ratios or S11 parameters in making this determination. To determine whether or not the match is acceptable, the system controller may compare the calculated ratio and/or S11 parameter to a threshold, for example. For example, in one embodiment, the system controller may compare the calculated reflected-to-forward signal power ratio to a threshold of 10 percent (or some other value). A ratio below 10 percent may indicate that the match remains acceptable, and a ratio above 10 percent may indicate that the match is no longer acceptable. When the calculated ratio or S11 parameter is greater than the threshold (i.e., the comparison is unfavorable), indicating an unacceptable match, then the system controller may initiate re-configuration of the variable impedance matching network by again performing process **910**.

As discussed previously, the match provided by the variable impedance matching network may degrade over the course of a defrosting operation due to impedance changes of the load (e.g., load **316**, FIG. **3**) as the load warms up. It has been observed that, over the course of a defrosting operation, an optimal cavity match may be maintained by decreasing the cavity match inductance (e.g., by decreasing the inductance of variable inductance network **411**, FIG. **4**) and by increasing the RF signal source inductance (e.g., by increasing the inductance of variable inductance network **410**, FIG. **4**). Referring again to FIG. **10**, for example, an optimal match for the first type of load at the end of a defrosting operation is indicated by point **1014**, and an optimal match for the second type of load at the end of a defrosting operation is indicated by point **1024**. In both cases, tracking of the optimal match between initiation and completion of the defrosting operations involves gradually decreasing the inductance of the cavity match and increasing the inductance of the RF signal source match.

According to an embodiment, in the iterative process **910** of re-configuring the variable impedance matching network, the system controller may take into consideration this tendency. More particularly, when adjusting the match by reconfiguring the variable impedance matching network in block **918**, the system controller initially may select states of the variable inductance networks for the cavity and RF signal source matches that correspond to lower inductances (for the cavity match, or network **411**, FIG. **4**) and higher inductances (for the RF signal source match, or network **410**, FIG. **4**). By selecting impedances that tend to follow the expected optimal match trajectories (e.g., those illustrated in FIG. **10**), the time to perform the variable impedance matching network reconfiguration process **910** may be reduced, when compared with a reconfiguration process that does not take these tendencies into account.

In an alternate embodiment, the system controller may instead iteratively test each adjacent configuration to attempt to determine an acceptable configuration. For example, referring again to Table 1, above, if the current configuration corresponds to state 12 for the cavity matching network and to state 3 for the RF signal source matching network, the system controller may test states 11 and/or 13 for the cavity matching network, and may test states 2 and/or 4 for the RF signal source matching network. If those tests do not yield a favorable result (i.e., an acceptable match), the system controller may test states 10 and/or 14 for the cavity matching network, and may test states 1 and/or 5 for the RF signal source matching network, and so on.

In actuality, there are a variety of different searching methods that the system controller may employ to reconfigure the system to have an acceptable impedance match, including testing all possible variable impedance matching network configurations. Any reasonable method of searching for an acceptable configuration is considered to fall within the scope of the inventive subject matter. In any event, once an acceptable match is determined in block **916**, the defrosting operation is resumed in block **920**, and the process continues to iterate.

Referring back to block **924**, when the system controller determines, based on one or more calculated reflected-to-forward signal power ratios and/or one or more calculated S11 parameters, that the match provided by the variable impedance matching network is still acceptable (e.g., the calculated ratio or S11 parameter is less than the threshold, or the comparison is favorable), the system may evaluate whether or not an exit condition has occurred, in block **926**. In actuality, determination of whether an exit condition has occurred may be an interrupt driven process that may occur at any point during the defrosting process. However, for the purposes of including it in the flowchart of FIG. **9**, the process is shown to occur after block **924**.

In any event, several conditions may warrant cessation of the defrosting operation. For example, the system may determine that an exit condition has occurred when a safety interlock is breached. Alternatively, the system may determine that an exit condition has occurred upon expiration of a timer that was set by the user (e.g., through user interface **320**, FIG. **3**) or upon expiration of a timer that was established by the system controller based on the system controller's estimate of how long the defrosting operation should be performed. In still another alternate embodiment, and as will be explained in more detail in conjunction with FIGS. **11** and **12**, the system may otherwise detect completion of the defrosting operation.

If an exit condition has not occurred, then the defrosting operation may continue by iteratively performing blocks **922** and **924** (and the matching network reconfiguration process **910**, as necessary). When an exit condition has occurred, then in block **928**, the system controller causes the supply of the RF signal by the RF signal source to be discontinued. For example, the system controller may disable the RF signal generator (e.g., RF signal generator **342**, FIG. **3**) and/or may cause the power supply and bias circuitry (e.g., circuitry **350**, FIG. **3**) to discontinue provision of the supply current. In addition, the system controller may send signals to the user interface (e.g., user interface **320**, FIG. **3**) that cause the user interface to produce a user-perceptible indicia of the exit condition (e.g., by displaying "door open" or "done" on a display device, or providing an audible tone). The method may then end.

As indicated above, the defrosting system may be configured to determine when a defrosting operation has completed. More specifically, the defrosting system may be configured to estimate a time when a previously-frozen load has reached a desired state of defrost. For example, a desired state of defrost may be a state in which the average temperature of the load is in a range of about −4 degrees Celsius to about −2 degrees Celsius. Alternatively, a desired state of defrost may be a state in which the average temperature of the load is in a range of about −2 degrees Celsius to about 0 degrees Celsius. A desired state of defrost may be a state when the load is at another temperature or temperature range, as well.

According to an embodiment, a method of determining completion of a defrosting operation is based on observations of the rates of impedance changes for the load throughout a defrosting operation in comparison with observed typical impedance change rates of known loads during defrosting operations. To facilitate understanding of the method embodiments, a chart illustrating a typical impedance change response for a typical load is provided in FIG. **11**. More specifically, FIG. **11** is a chart plotting load temperature versus rate of reflected-to-forward power ratio (R/F ratio) change or S11 parameter change for a typical load.

As trace **1110** indicates, the rate of change of reflected-to-forward power ratio or S11 parameter (e.g., as measured by power detection circuitry **380** and calculated by system controller **330**, FIG. **3**) may increase rapidly at the beginning of a defrosting operation when the average load temperature falls within a relatively low temperature range **1120** (e.g., a range of temperatures between about −20 degrees Celsius and −15 degrees Celsius). As used herein, this low temperature range **1120** is referred to as a "sub-plateau temperature range". As the average load temperature increases above a first temperature threshold **1122** (referred to herein as a "lower plateau temperature limit"), the rate of change of reflected-to-forward power ratio or S11 parameter decreases markedly and stabilizes to a relatively constant rate (i.e., the rate of change hits a "plateau"). This lower and relatively stable rate of change, referred to herein as a "plateau rate," may be observed through a relatively wide second temperature range **1130**, referred to herein as a "plateau temperature range." For example, the plateau temperature range **1130** may extend between about −15 degrees Celsius and about −3 degrees Celsius, and the upper temperature threshold of the plateau temperature range **1130** is referred to herein as the "upper plateau temperature limit" **1132**. Alternatively, the plateau temperature range may be more narrowly defined (e.g., as including a range of temperatures between about −8 degrees Celsius and about −4 degrees Celsius). Further, at temperatures above the plateau temperature range **1130** (i.e., above the upper plateau temperature limit **1132**) the rate of change of reflected-to-forward power ratio or S11 parameter again begins to increase rapidly. For example, high rates of change of reflected-to-forward power ratio or S11 parameter may begin to occur at about −3 degrees Celsius, and may continue through a "super-plateau temperature range" **1140** that extends to and beyond 0 degrees Celsius.

As will be described in detail below in conjunction with FIG. **12**, the system controller may monitor the rate of change of forward-to-reflected power or S11 parameter to determine a time at which the defrosting operation is considered to be completed, and should be halted. More particularly, FIG. **12**, which includes FIGS. **12**A and **12**B, is a flowchart of a method of operating a defrosting system (e.g., system **100**, **210**, **220**, **300**, **700**, FIGS. **1-3**, **7**) with automatic detection of the end of a defrosting operation, in accordance with an example embodiment. A number of the operations performed in the method of FIG. **12** are substantially similar to corresponding operations performed in the method of FIG. **9**. Where such similarities exist, they will be pointed out, and the details of such operations will not be discussed in detail below for the purpose of brevity. It should be understood that the details discussed in conjunction with the operations of FIG. **9** apply equally to the similar operations of FIG. **12**.

Referring first to FIG. **12**A, and according to an embodiment, the method may begin, in block **1202** (substantially similar to block **902**, FIG. **9**), when the system controller (e.g., system controller **330**, FIG. **3**) receives an indication that a defrosting operation should start. According to various embodiments, the system controller also and optionally may receive additional inputs indicating the load type (e.g., meats, liquids, or other materials), the initial load temperature, and/or the load weight. As discussed above, receipt of inputs indicating the load type, initial load temperature, and/or load weight is optional, and the system alternatively may not receive some or all of these inputs.

In block **1204** (substantially similar to block **904**, FIG. **9**), the system controller provides control signals to the variable matching network (e.g., network **360**, **400**, FIGS. **3**, **4**) to establish an initial configuration or state for the variable matching network. Once the initial variable matching network configuration is established, the system controller then may perform a process **1210** (substantially similar to process **910**, FIG. **9**) of adjusting, if necessary, the configuration of the variable impedance matching network to find an acceptable or best match based on actual measurements that are indicative of the quality of the match.

Once an acceptable or best match is determined, the defrosting operation may commence. Commencement of the defrosting operation includes increasing the power of the RF signal supplied by the RF signal source (e.g., RF signal source **340**) to a relatively high power RF signal, in block **1212** (substantially similar to block **920**, FIG. **9**).

According to an embodiment, if the system controller is in possession of a starting temperature measurement for the load (e.g., received from a temperature or IR sensor **390**, **792**, FIGS. **3**, **7**), the system may make a determination, in block **1214**, of whether or not the starting temperature is greater than a lower plateau temperature limit (e.g., temperature **1122**, FIG. **11**). If not, then the system performs an initial defrosting operation while the temperature of the load is within the sub-plateau temperature range (e.g., range **1120**, FIG. **11**). More specifically, in block **1216** (substantially similar to block **922**, FIG. **9**), power detection circuitry (e.g., power detection circuitry **380**, FIG. **3**) periodically measures the forward and reflected power along the transmission path (e.g., path **348**, FIG. **3**) between the RF signal source and the first electrode, and provides those measurements to the system controller. The system controller may determine a ratio between the reflected and forward signal powers, and may determine the S11 parameter for the system based on the ratio. According to an embodiment, the system controller stores a plurality of the calculated ratios and/or S11 parameters for use in determining the rates of change of the calculated ratios and/or S11 parameters.

In block **1218** (substantially similar to block **924**, FIG. **9**), the system controller may determine, based on one or more calculated reflected-to-forward signal power ratios and/or one or more calculated S11 parameters, whether or not the current match provided by the variable impedance matching network is acceptable. To determine whether or not the match is acceptable, the system controller may compare the calculated ratio and/or S11 parameter to a threshold, in an embodiment. For example, in one embodiment, the system controller may compare the calculated reflected-to-forward signal power ratio to a threshold of 10 percent (or some other value). A ratio below 10 percent may indicate that the match remains acceptable, and a ratio above 10 percent may indicate that the match is no longer acceptable. When the calculated ratio or S11 parameter is greater than the threshold (i.e., the comparison is unfavorable), indicating an unacceptable match, then the system controller may initiate re-configuration of the variable impedance matching network by again performing process **1210**.

Referring back to block **1218**, when the system controller determines, based on one or more calculated reflected-to-forward signal power ratios and/or one or more calculated S11 parameters, that the match provided by the variable impedance matching network is still acceptable (e.g., the calculated ratio or S11 parameter is less than the threshold, or the comparison is favorable), then the system controller may calculate, in block **1220**, the rate of change of the reflected-to-forward power ratio (or the rate of change of the S11 parameter). For example, the rate of change may be calculated by performing a mathematical calculation (e.g., calculating an average or standard deviation) using a number, X, of the most recently calculated ratios, where X may be an integer in a range of 2 to 10, for example. In other words, the system controller calculates the rate of change of the reflected-to-forward power ratio (or the rate of change of the S11 parameter) by performing the mathematical calculation on a sliding window of the X most recently calculated ratios.

According to another embodiment, the system controller may quantify the rate of change of the reflected-to-forward power ratio (or the rate of change of the S11 parameter) in terms of how frequently the matching network is re-configured (i.e., in block **1210**). A low frequency of re-configuring the matching network implies that the reflected-to-forward power ratio is not changing significantly at a rapid rate. Conversely, a high frequency of re-configuring the matching network implies that the reflected-to-forward power ratio is changing significantly at a rapid rate.

In block **1222**, the system controller makes a determination of whether or not the rate of change of the reflected-to-forward power ratio (or the rate of change of the S11 parameter) is greater than the plateau rate. Alternatively, the system controller may make a determination of whether the frequency at which the matching network is re-configured exceeds a threshold (thus implying that the rate of change is greater than the plateau rate). As discussed previously in conjunction with FIG. **11**, the plateau rate is a relatively constant rate of change of reflected-to-forward signal power ratio (or S11 parameter) that a typical load may experience when the load temperature is within the plateau temperature range (e.g., plateau temperature range **1130**, FIG. **11**).

When the system controller determines that the rate of change is greater than the plateau rate, an assumption is made that the load temperature is still within the sub-plateau temperature range (e.g., range **1120**, FIG. **11**), and the process repeats blocks **1216**, **1218**, and **1220**. However, when the system controller first determines that the rate of change is not greater than the plateau rate, an assumption is made that the load temperature has transitioned into the plateau temperature range (e.g., range **1130**, FIG. **11**). At this point, the system controller begins monitoring the amount of time that the defrosting process is performed to predict completion of the process.

To this end, and continuing with block **1250** of FIG. **12**B, the system controller initializes and starts a "plateau region" count-down or count-up timer associated with monitoring the amount of time that the system is performing the defrosting operation. As an assumption is made that the load temperature has just entered the plateau temperature range (e.g., temperature range **1130**, FIG. **11**), the timer essentially is used to keep track of how much time the system is performing the defrosting operation while the load temperature is within the plateau temperature range. Alternatively, rather than using a timer, the system controller may initialize a counter that monitors a number of times that the reflected-to-forward power ratio (or S11 parameter) is calculated (e.g., in block **1252**). In either case, the system assumes that the defrosting operation will be completed when the plateau region timer or counter reaches a particular limit, as will be determined later (in block **1260**).

According to an embodiment, the system determines the limit to correspond to an amount of time (or a number of counts) that it will take the system to provide enough RF power to the load to increase the temperature of the load to a desired defrost cessation temperature (e.g., the upper plateau temperature limit **1132**, FIG. **11**, or some lower or higher temperature). The amount of time to get the load to the defrost cessation temperature depends on the quantity of RF power that is absorbed by the load (which is a reflection of the quality of the match and the cumulative duration of time that the RF power is provided), the weight of the load, and the material characteristics of the load. These variables may be determined or estimated by the system controller through measurement and analysis, and/or may be determined or estimated by the system controller based on user-provided or sensor-provided information. In any event, and according to an embodiment, the plateau region timer or counter may be controlled to expire after a period of time in a range of about 5 minutes (e.g., for smaller or lower impedance loads) to about 20 minutes (e.g., for larger or more high impedance loads), although the timer or counter may be controlled to expire after shorter or longer durations of time, as well.

In block **1252** (substantially similar to block **922**, FIG. **9**), power detection circuitry (e.g., power detection circuitry **380**, FIG. **3**) begins to periodically measure the forward and reflected power along the transmission path (e.g., path **348**, FIG. **3**) between the RF signal source and the first electrode, and provide those measurements to the system controller. The system controller again may determine a ratio between the reflected and forward signal powers, and may determine the S11 parameter for the system based on the ratio. The system controller may store the calculated ratios and/or S11 parameters for future evaluation or comparison, in an embodiment.

In block **1254** (substantially similar to block **924**, FIG. **9**), the system controller again may determine, based on one or more calculated reflected-to-forward signal power ratios and/or one or more calculated S11 parameters, whether or not the match provided by the variable impedance matching network is acceptable. For example, the system controller may use a single calculated reflected-to-forward signal power ratio or S11 parameter in making this determination, or may take an average (or other calculation) of a number of previously-calculated reflected-to-forward power ratios or S11 parameters in making this determination. To determine whether or not the match is acceptable, the system controller may compare the calculated ratio and/or S11 parameter to a threshold, for example.

In addition, the system controller may increment the plateau region timer (although this may be done continuously, as well), or may increment the plateau region counter (e.g., indicating a number of times that the reflected-to-forward power ratio has been calculated.

When the calculated ratio or S11 parameter is greater than the threshold (i.e., the comparison is unfavorable), indicating an unacceptable match, then the system controller may initiate re-configuration of the variable impedance matching network by performing process **1256** (substantially similar to process **910**, FIG. **9**). According to an embodiment, the plateau region timer may be paused while the matching network is being re-configured. Once an acceptable match has been achieved by re-configuring the variable impedance matching network, the system may resume the defrosting process by performing block **1258** (substantially similar to block **920**, FIG. **9**), in which the system controller causes an increase in the power of the RF signal supplied by the RF signal source (e.g., RF signal source **340**) to a relatively high power RF signal. The system then returns to block **1252**.

Referring again to block **1254**, when the calculated ratio or S11 parameter is not greater than the threshold (i.e., the comparison is favorable), indicating an acceptable match, then the system controller may make a determination, in block **1260**, of whether or not the plateau region timer/counter is less than the limit (or the timer has not expired).

If the plateau region timer/counter is not less than the limit (or has expired), then the system controller may determine that the defrosting process has completed. When the system controller has determined that the defrosting process has completed, then in block **1266**, the system controller causes the supply of the RF signal by the RF signal source to be discontinued. For example, the system controller may disable the RF signal generator (e.g., RF signal generator **342**, FIG. **3**) and/or may cause the power supply and bias circuitry (e.g., circuitry **350**, FIG. **3**) to discontinue provision of the supply current. In addition, the system controller may send signals to the user interface (e.g., user interface **320**, FIG. **3**) that cause the user interface to produce a user-perceptible indicia of the completion of the defrosting process (e.g., by displaying "done" on a display device, or providing an audible tone). The method may then end.

If the plateau region timer/counter is less than the limit (or has not expired), then in block **1262** (substantially similar to block **1220**, described above), the system controller may calculate the rate of change of the reflected-to-forward power ratio (or the rate of change of the S11 parameter). Again, for example, the rate of change may be calculated by performing a mathematical calculation (e.g., calculating an average or standard deviation) using a number, X, of the most recently calculated ratios. According to another embodiment, the system controller may quantify the rate of change of the reflected-to-forward power ratio (or the rate of change of the S11 parameter) in terms of how frequently the matching network is re-configured (i.e., in block **1256**).

In block **1264**, the system controller makes a determination of whether or not the rate of change of the reflected-to-forward power ratio (or the rate of change of the S11 parameter) is greater than the plateau rate. Alternatively, the system controller may make a determination of whether the frequency at which the matching network is re-configured exceeds a threshold (thus implying that the rate of change is greater than the plateau rate).

When the system controller determines that the rate of change is not greater than the plateau rate (or the rate of change compares favorably with the plateau rate), an assumption is made that the load temperature is still within the plateau temperature range (e.g., range **1130**, FIG. **11**), and the process repeats blocks **1252**, **1254**, and **1260**. However, if the system controller determines that the rate of change is greater than the plateau rate (or the rate of change compares unfavorably with the plateau rate), an assumption is made that the load temperature has transitioned into the super-plateau temperature range (e.g., range **1140**, FIG. **11**). At this point, the system controller may determine that the defrosting process has completed.

Again, when the system controller has determined that the defrosting process has completed, then in block **1266**, the system controller causes the supply of the RF signal by the RF signal source to be discontinued, and the system controller may send signals to the user interface (e.g., user interface **320**, FIG. **3**) that cause the user interface to produce a user-perceptible indicia of the completion of the defrosting process (e.g., by displaying "done" on a display device, or providing an audible tone). As discussed previously in conjunction with the flowchart of FIG. **9**, other exit conditions also may cause the system controller to discontinue a defrosting operation, as well. Either way, once the defrosting operation is terminated, the method may end.

It should be understood that the order of operations associated with the blocks depicted in FIGS. **9** and **12** corresponds to example embodiments, and should not be construed to limit the sequence of operations only to the illustrated orders. Instead, some operations may be performed in different orders, and/or some operations may be performed in parallel.

The connecting lines shown in the various figures contained herein are intended to represent exemplary functional relationships and/or physical couplings between the various elements. It should be noted that many alternative or additional functional relationships or physical connections may be present in an embodiment of the subject matter. In addition, certain terminology may also be used herein for the purpose of reference only, and thus are not intended to be limiting, and the terms "first", "second" and other such numerical terms referring to structures do not imply a sequence or order unless clearly indicated by the context.

As used herein, a "node" means any internal or external reference point, connection point, junction, signal line, conductive element, or the like, at which a given signal, logic level, voltage, data pattern, current, or quantity is present. Furthermore, two or more nodes may be realized by one physical element (and two or more signals can be multiplexed, modulated, or otherwise distinguished even though received or output at a common node).

The foregoing description refers to elements or nodes or features being "connected" or "coupled" together. As used herein, unless expressly stated otherwise, "connected" means that one element is directly joined to (or directly communicates with) another element, and not necessarily mechanically. Likewise, unless expressly stated otherwise, "coupled" means that one element is directly or indirectly joined to (or directly or indirectly communicates with) another element, and not necessarily mechanically. Thus, although the schematic shown in the figures depict one exemplary arrangement of elements, additional intervening elements, devices, features, or components may be present in an embodiment of the depicted subject matter.

An embodiment of a method of performing a thermal increase operation (or a defrosting operation) on a load that is positioned within a cavity of a thermal increase system includes providing, by an RF signal source through a transmission path, an RF signal to an electrode that is proximate to the cavity. The method further includes repeatedly taking forward RF power measurements and reflected RF power measurements along the transmission path, repeatedly determining, based on the forward RF power measurements and the reflected RF power measurements, a calculated rate of change, and repeatedly comparing the calculated rate of change to a threshold rate of change. When a determination is made that the calculated rate of change compares favorably with the threshold rate of change, the method further includes continuing to provide the RF signal to the electrode until a determination is made that the thermal increase operation is completed. When the determination is made that the thermal increase operation is completed, provision of the RF signal to the electrode is ceased. The RF signal may be an oscillating signal having a frequency between 3.0 megahertz and 300 megahertz. The RF signal may be an oscillating signal having a frequency selected from 13.56 megahertz (+/−5 percent), 27.125 megahertz (+/−5 percent), and 40.68 megahertz (+/−5 percent). Determining the calculated rate of change may comprise: calculating a plurality of ratios of the reflected RF power measurements to the forward RF power measurements; and determining the calculated rate as a rate at which the plurality of ratios changes over time. Determining the calculated rate of change may comprise: calculating a plurality of ratios of the reflected RF power measurements to the forward RF power measurements; calculating a plurality of S11 parameters from the plurality of ratios; and determining the calculated rate as a rate at which the plurality of S11 parameters changes over time. The threshold rate of change may be a rate of change that is consistent with the load having a temperature that is within a plateau temperature range. The plateau temperature range may include a range of temperatures between −16 degrees Celsius and −3 degrees Celsius. The plateau temperature range may include a range of temperatures between −8 degrees Celsius and −4 degrees Celsius. Making the determination that the thermal increase operation is completed may comprise determining whether a timer has expired. The thermal increase system may include a variable impedance matching network between the RF signal source and the electrode, and wherein making the determination that the thermal increase operation is completed comprises determining whether a rate at which the variable impedance matching network is re-configured to improve matching between the RF signal source and the cavity plus the load. The thermal increase system may include a variable impedance matching network between the RF signal source and the first electrode, the method further comprising: repeatedly calculating ratios of the reflected RF power measurements to the forward RF power measurements; repeatedly comparing the ratios to a threshold; and when a ratio of a reflected RF power measurement to a forward RF power measurement compares unfavorably with the threshold, re-configuring the variable impedance matching network to improve matching between the RF signal source and the cavity plus the load.

An embodiment of a thermal increase system (or defrosting system) is configured to perform a thermal increase operation (or defrost operation) on a load positioned within a cavity of the thermal increase system. The system includes an RF signal source configured to produce an RF signal, and a transmission path between the RF signal source and an electrode that is positioned proximate to the cavity, where the transmission path is configured to convey the RF signal from the RF signal source to the electrode. The system further includes power detection circuitry coupled to the transmission path and configured repeatedly to take forward RF power measurements and reflected RF power measurements along the transmission path, and a system controller coupled to the power detection circuitry. The system controller is configured to repeatedly determine, based on the forward RF power measurements and the reflected RF power measurements, a calculated rate of change, and to repeatedly compare the calculated rate of change to a threshold rate of change. When a determination is made that the calculated rate of change compares favorably with the threshold rate of change, the system controller is configured to enable the RF signal source to continue to provide the RF signal to the electrode until a determination is made that the thermal increase operation is completed. When the determination is made that the thermal increase operation is completed, the system controller is configured to cause the RF signal source to cease provision of the RF signal to the electrode.

The system controller may be configured to determine the calculated rate of change by: calculating a plurality of ratios of the reflected RF power measurements to the forward RF power measurements; calculating a plurality of S11 parameters from the plurality of ratios; and determining the calculated rate as a rate at which the plurality of S11 parameters changes over time. The threshold rate of change may be a rate of change that is consistent with the load having a temperature that is within a plateau temperature range. The plateau temperature range may include a range of temperatures between −16 degrees Celsius and −3 degrees Celsius. The plateau temperature range may include a range of temperatures between −8 degrees Celsius and −4 degrees Celsius. The system may further comprise: a timer, wherein making the determination that the thermal increase operation is completed comprises determining whether the timer has expired. The system may further comprise: a variable impedance matching network coupled between the RF signal source and the electrode, wherein the system controller is configured to make the determination that the thermal increase operation is completed by determining a rate at which the variable impedance matching network is re-configured to improve matching between the RF signal source and the cavity plus the load. The system may further comprise: a variable impedance matching network between the RF signal source and the first electrode,

wherein the system controller is configured to repeatedly calculate ratios of the reflected RF power measurements to the forward RF power measurements, repeatedly compare the ratios to a threshold, and when a ratio of a reflected RF power measurement to a forward RF power measurement compares unfavorably with the threshold, to re-configure the variable impedance matching network to improve matching between the RF signal source and the cavity plus the load.

While at least one exemplary embodiment has been presented in the foregoing detailed description, it should be appreciated that a vast number of variations exist. It should also be appreciated that the exemplary embodiment or embodiments described herein are not intended to limit the scope, applicability, or configuration of the claimed subject matter in any way. Rather, the foregoing detailed description will provide those skilled in the art with a convenient road map for implementing the described embodiment or embodiments. It should be understood that various changes can be made in the function and arrangement of elements without departing from the scope defined by the claims, which includes known equivalents and foreseeable equivalents at the time of filing this patent application.

The invention claimed is:

1. A method of performing a thermal increase operation on a load that is positioned within a cavity of a thermal increase system, the method comprising:

providing, by a radio frequency (RF) signal source through a transmission path, an RF signal to an electrode that is proximate to the cavity;

repeatedly taking forward RF power measurements and reflected RF power measurements along the transmission path, calculating ratios of the reflected RF power measurements to the forward RF power measurements, and comparing the ratios to a threshold ratio;

when a ratio of a reflected RF power measurement to a forward RF power measurement is greater than the threshold ratio, re-configuring a variable impedance matching network between the RF signal source and the electrode to improve matching between the RF signal source and the cavity plus the load and reduce the ratio below the threshold ratio;

repeatedly determining a frequency at which the variable impedance matching network is re-configured;

repeatedly comparing the frequency to a threshold frequency;

when a determination is made that the frequency is not greater than the threshold frequency, initializing a timer associated with monitoring an amount of time that the RF signal source is to continue to provide the RF signal;

continuing to provide the RF signal to the electrode until a determination is made that the timer has expired; and

when the determination is made that the timer has expired, ceasing provision of the RF signal to the electrode.

2. The method as claimed in claim **1**, wherein the threshold frequency is a frequency that is consistent with the load having a temperature that is within a plateau temperature range.

3. The method as claimed in claim **2**, wherein the plateau temperature range includes a range of temperatures between −16 degrees Celsius and −3 degrees Celsius.

4. The method as claimed in claim **3**, wherein the plateau temperature range includes a range of temperatures between −8 degrees Celsius and −4 degrees Celsius.

5. The method as claimed in claim **1**, wherein:

the RF signal is an oscillating signal having a frequency between 3.0 megahertz and 300 megahertz.

6. The method as claimed in claim **5**, wherein:

the RF signal is an oscillating signal having a frequency selected from 13.56 megahertz (+/−5 percent), 27.125 megahertz (+/−5 percent), and 40.68 megahertz (+/−5 percent).

7. The method as claimed in claim **1**, further comprising:

while continuing to provide the RF signal until the determination is made, also continuing to calculate the ratios of the reflected RF power measurements to the forward RF power measurements, continuing to compare the ratios to the threshold, and continuing to re-configure the variable impedance matching network when the ratio is greater than the threshold; and

pausing the timer while re-configuring the variable impedance matching network.

8. A thermal increase system configured to perform a thermal increase operation on a load positioned within a cavity of the thermal increase system, the system comprising:

a radio frequency (RF) signal source configured to produce an RF signal;

a transmission path between the RF signal source and an electrode that is positioned proximate to the cavity, wherein the transmission path is configured to convey the RF signal from the RF signal source to the electrode;

a variable impedance matching network along the transmission path;

power detection circuitry coupled to the transmission path and configured repeatedly to take forward RF power measurements and reflected RF power measurements along the transmission path; and

a system controller coupled to the power detection circuitry, wherein the system controller is configured

to repeatedly calculate ratios of the reflected RF power measurements to the forward RF power measurements, and compare the ratios to a threshold ratio,

when a ratio of a reflected RF power measurement to a forward RF power measurement is greater than the threshold ratio, to re-configure the variable impedance matching network to improve matching between the RF signal source and the cavity plus the load and reduce the ratio below the threshold ratio,

to repeatedly determine a frequency at which the variable impedance matching network is re-configured,

to repeatedly compare the frequency to a threshold frequency,

when the system controller determines that the frequency is not greater than the threshold frequency, to initialize a timer associated with monitoring an amount of time that the RF signal source is to continue to produce the RF signal;

wherein the RF signal source is configured to continue to provide the RF signal to the electrode until the system controller makes a determination that the timer has expired; and

the system controller is configured to cause the RF signal source to cease provision of the RF signal to the electrode when the system controller makes the determination that the timer has expired.

9. The system as claimed in claim **8**, wherein:

the RF signal source is configured to produce the RF signal as an oscillating signal having a frequency between 3.0 megahertz and 300 megahertz.

10. The system as claimed in claim **9**, wherein:

the RF signal is an oscillating signal having a frequency selected from 13.56 megahertz (+/−5 percent), 27.125 megahertz (+/−5 percent), and 40.68 megahertz (+/−5 percent).

11. The system as claimed in claim **8**, wherein the threshold frequency is a frequency that is consistent with the load having a temperature that is within a plateau temperature range.

12. The system as claimed in claim **11**, wherein the plateau temperature range includes a range of temperatures between −16 degrees Celsius and −3 degrees Celsius.

13. The system as claimed in claim **12**, wherein the plateau temperature range includes a range of temperatures between −8 degrees Celsius and −4 degrees Celsius.

14. The system as claimed in claim **8**, wherein the system further comprises:

the timer.

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